SCIENCE AND TECHNOLOGY

JET PROPULSION

A publication of the
AMERICAN ROCKET SOCIETY
Research and Development

STACKS

VOLUME 27 SEPTEMBER 1957 NUMBER 9

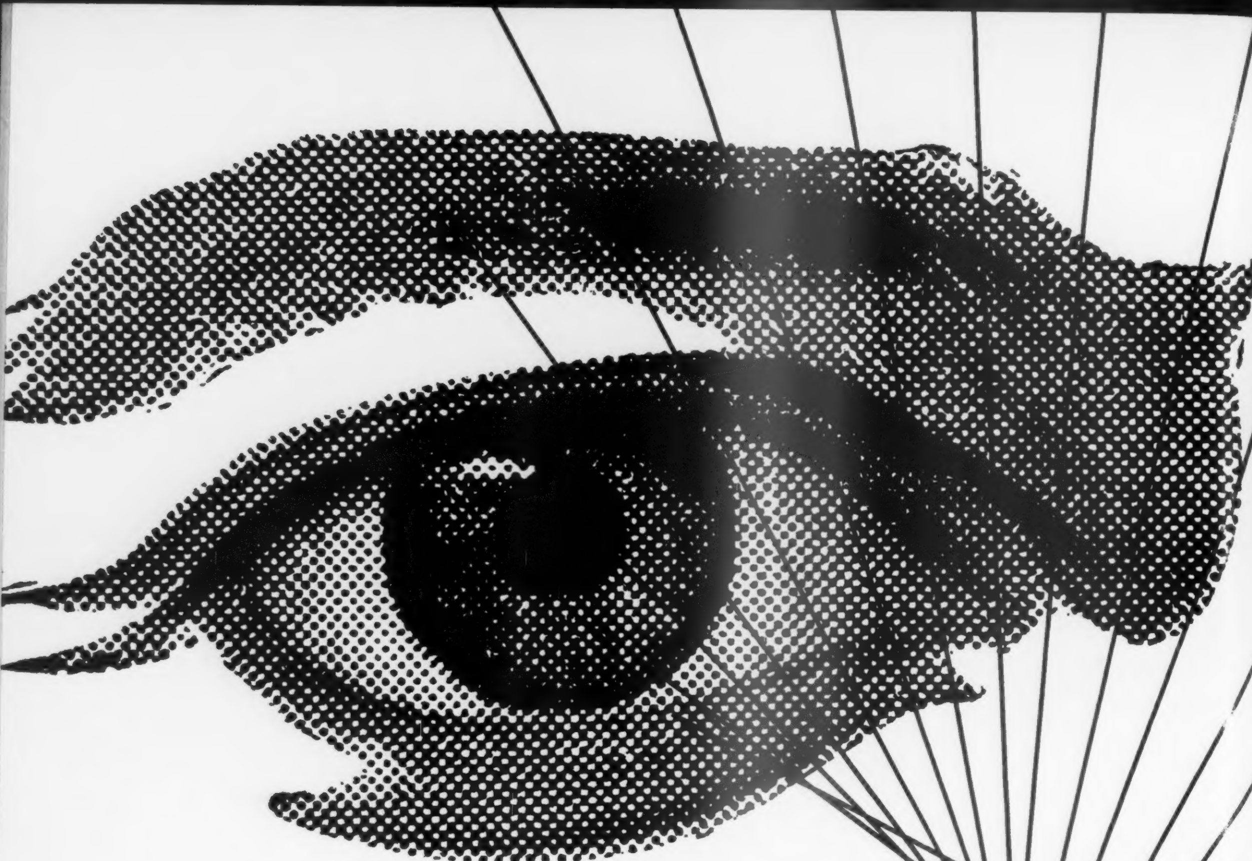
HIGH SPEED EXPERIMENTAL TRACKS ISSUE

TRACK AND SLED DESIGN

TRACK INSTRUMENTATION

TEST PROGRAMS ON HIGH SPEED TRACKS

DEPARTMENTS



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Inquisitive eyes denote the inquisitive minds that made possible today's rocket powerplants. Sharp eyes and minds that have the power to visualize challenging problems . . . *and* the insight to solve them.

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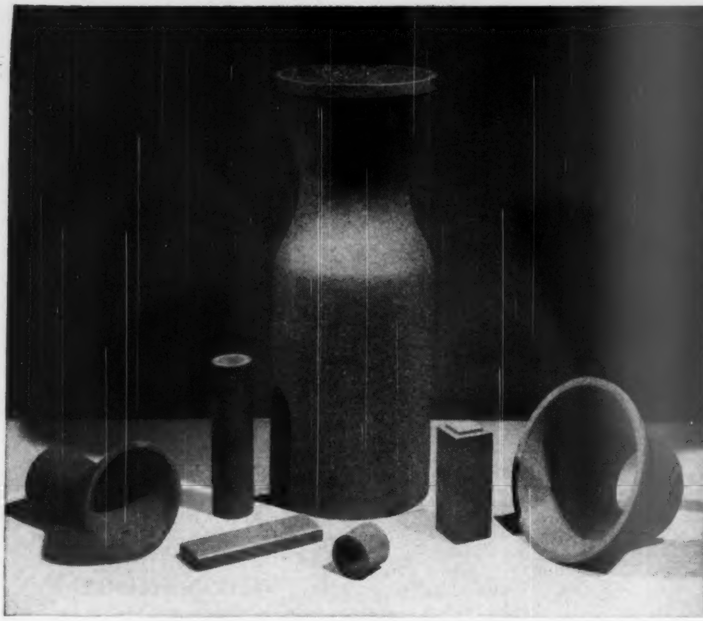
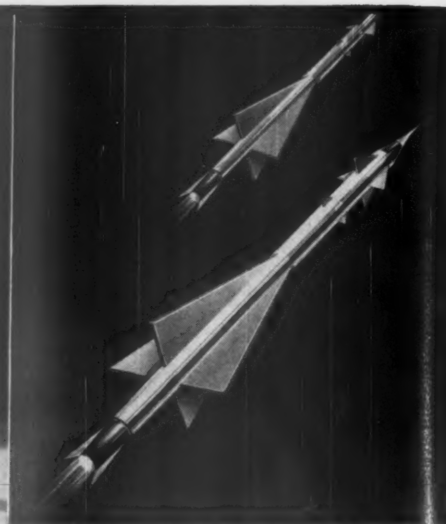




Rocket Motors, Nozzles and Other Components for reaction motors — made to stand up under extremes of temperature, heat shock and erosion.

NEW CERAMIC COATINGS & COMPONENTS FOR MISSILES AND ROCKETS

To meet the exacting requirements and to aid the performance of reaction motors, Norton Company has developed several new silicon carbide products. Among these are: ROKIDE* "C" silicon carbide coating on graphite; CRYSTOLON* "R" recrystallized silicon carbide and CRYSTOLON "N" nitride-bonded silicon carbide bodies.

ROKIDE "C"
Silicon Carbide Coating

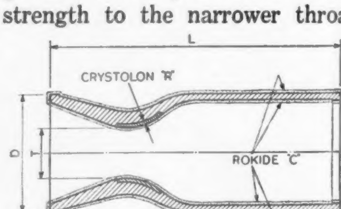
This hard, crystalline coating protects light weight, thermal shock resistant graphite — gives it excellent resistance to erosion and oxidation — and makes it highly suited for use in rocket motors. ROKIDE "C" coating on graphite has found ready use for combustion chambers and exit cones of uncooled rocket motors as well as for ramjet exhaust nozzles.

CRYSTOLON "R" and "N"
Silicon Carbide Bodies

Components of CRYSTOLON "R" recrystallized silicon carbide and CRYSTOLON "N" nitride-bonded silicon carbide have excellent erosion, thermal shock and oxidation resistance, good strength, low density and thermal conductivity. They can be made in a wide variety of shapes and sizes.

TWO-WAY PROTECTION IN A ROCKET MOTOR

ROKIDE "C" coating protects this entire rocket motor, while CRYSTOLON "R" silicon carbide gives added protection and strength to the narrower throat



area where conditions are most severe.

DIMENSIONAL LIMITS

	Diameters	Lengths	Throats
ROKIDE "C" / CRYSTOLON "R"	½" to 24"	½" to 30"	3/16" to 22"
CRYSTOLON "N"	¾" to 18"	¾" to 20"	3/8" to 16"

For further information on these NORTON developments for reaction motors, write to NORTON COMPANY, New Products Department, 728 New Bond Street, Worcester 6, Massachusetts.

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Scope of JET PROPULSION

This Journal is a publication of the American Rocket Society devoted to the advancement of the field of jet propulsion through the dissemination of original papers disclosing new knowledge or new developments. As used herein, the term "jet propulsion" embraces all engines that develop thrust by rearward discharge of a jet through a nozzle or duct, and thus it includes air-consuming engines and underwater systems as well as rockets. JET PROPULSION is open to contributions dealing not only with propulsion but with other aspects of jet-propelled flight, such as flight mechanics, guidance, telemetering, and research instrumentation. Increasing emphasis will be given to the scientific problems of extraterrestrial flight.

Information for Authors

Manuscripts must be as brief as the proper presentation of the ideas will allow. Exclusion of dispensable material and conciseness of expression will influence the Editors' acceptance of a manuscript. In terms of standard-size double-spaced typed pages, a typical maximum length is 22 pages of text (including equations), 1 page of references, 1 page of abstract, and 12 illustrations. Fewer illustrations permit more text, and vice versa. Greater length will be acceptable only in exceptional cases.

Short manuscripts, not more than one quarter of the maximum length stated for full articles, may qualify for publication as Technical Notes. They may be devoted either to new developments requiring prompt disclosure or to comments on previously published papers. Such manuscripts are usually published within two months of the date of receipt.

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Submit manuscripts in duplicate (original plus first carbon, with two sets of illustrations) to the Editor, Martin Summerfield, Professor of Aeronautical Engineering, Princeton University, Princeton, N. J. Preprints of papers presented at ARS national meetings are automatically considered for publication.

JET PROPULSION is published monthly by the American Rocket Society, Inc., and the American Interplanetary Society at 20th & Northampton Sts., Easton, Pa., U. S. A. Editorial offices: 500 Fifth Ave., New York 36, N. Y. Price: $12.50 per year, $2.00 per single copy. Entered as second-class matter at the Post Office at Easton, Pa. Notice of change of address should be sent to the Secretary, ARS, at least 30 days prior to publication. Opinions expressed herein are the authors' and do not necessarily reflect the views of the Editors or of the Society.
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JET PROPULSION

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Research and Development

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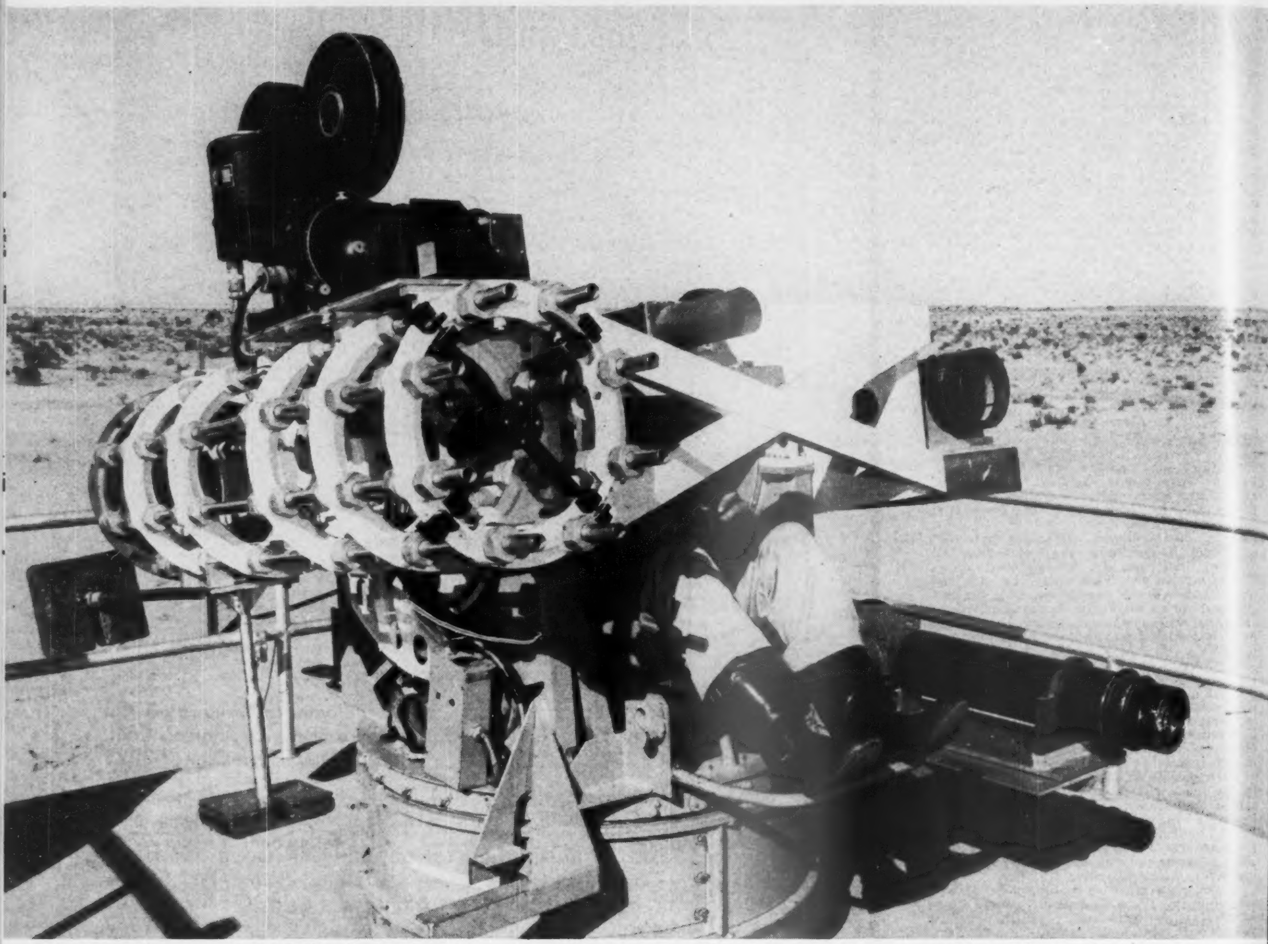
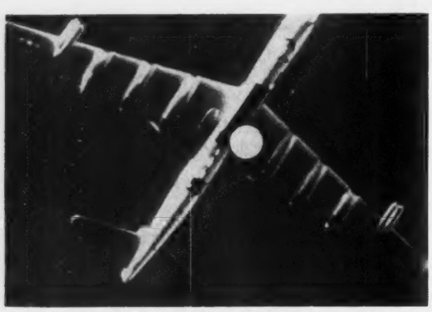


At the Atomic Energy Commission's Salton Sea Test Base this special tracking mount uses a 35mm high speed Mitchell camera. Operated by Sandia Corporation, this base uses Mitchell cameras for recording test operations.

Salton Sea Test Base Uses Mitchell Cameras to Capture High Speed Action of Dummy Bombs



Tracking at 40,000 feet, this film frame from a Mitchell camera operating at 96 frames per second provides an accurate record.

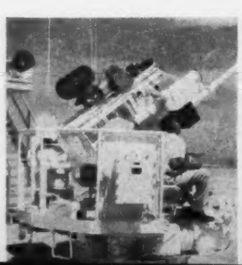
High speed flight and laboratory tests, which hitherto have been difficult or impossible to view with the human eye, are today providing revealing information through high speed film recordings.

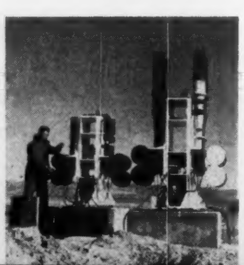
Typical example of the widespread use of high speed cameras is the Salton Sea Test Base in Southern California, where drop testing of "dummy" bombs is a major activity. In testing carried on there, by Sandia Corporation for the Atomic Energy Commission, as many as 20 Mitchell high speed cameras may record different angles in the flight of an experimental weapon "shape" from drop aircraft to impact area.

Operating at 48 to 100 frames per second, the Mitchell cameras film accurate, steady images with maximum uniformity—even under difficult and complicated filming conditions.

Mitchell cameras play a growing role in today's research and development—just as 16mm and 35mm Mitchell cameras have become the leading professional motion picture equipment used by industry, television, and film studios throughout the world. Write on your letterhead for further information on the uses of Mitchell cameras in the field of military and industrial research.

High speed Mitchell Camera in operation on tracking telescope mount during test run at Salton Sea.





Photogrammetric mounts for 8 Mitchell cameras determine the position in space of a nuclear explosion.

Mitchell Camera
CORPORATION
666 WEST HARVARD STREET
GLENDALE 4, CALIFORNIA
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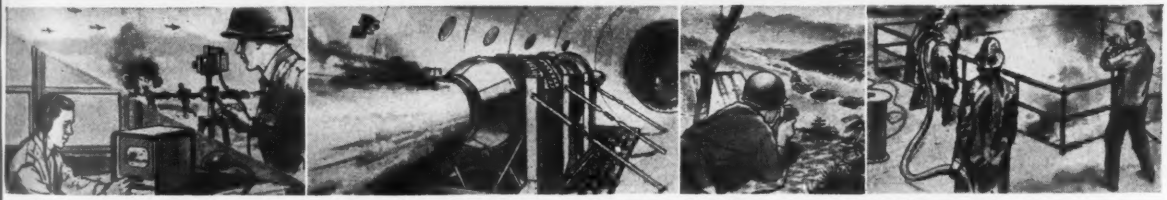
MIRACLE IN MINIATURE



Observation and control of amphibious and airborne landings.

Close observation of jet or piston engine test performance.

Surveillance of assembly areas and movements of forces.

Observation of danger areas, where exposure would involve danger to personnel.

Brand new! RCA "Telemite" (model JTV-1) a 1-pound ultra-miniature television camera, makes possible direct observation of sites and events never before accessible by TV

It fits lightly into the hand; it can be carried in a pocket; it weighs about a pound; it will go places too small for ordinary cameras, too dangerous for man; it will observe without being conspicuous; it may be mounted on a tripod, fastened to wall or bulkhead, hand-held by a pistol grip. Size: 1⅞" x 2⅜" x 4¾".

By means of a transistorized circuit and the new RCA half-inch Vidicon, the "Telemite" actually surpasses standard Vidicon-type industrial TV cameras in sensitivity. It produces clear, contrasty pictures with a scene illumination of 10-foot candles or less.

The "Telemite" operates with up to 200 feet of cable between it and the control monitor, and this distance can be further extended by using a repeater amplifier. This is the first TV camera to employ photoelectric sensitivity control, which provides automatic adaptation to widely varying scene illumination.

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Oxidant for liquid rocket propellants

Molecular weight	92.02
Boiling Point	21°C
Freezing Point	−11.3°C
Latent Heat of Vaporization	99 cal/gm @ 21°C
Critical Temp.	158°C
Critical Pressure	99 atm
Specific Heat of Liquid	0.36 cal/gm −10 to 20°C
Density of Liquid	1.45 at 20°C
Density of Gas	3.3 gm/liter 21°C. at 1 atm
Vapor Pressure	2 atm at 35°C

"Photo courtesy of Rocketdyne, a Division of North American Aviation, Inc."

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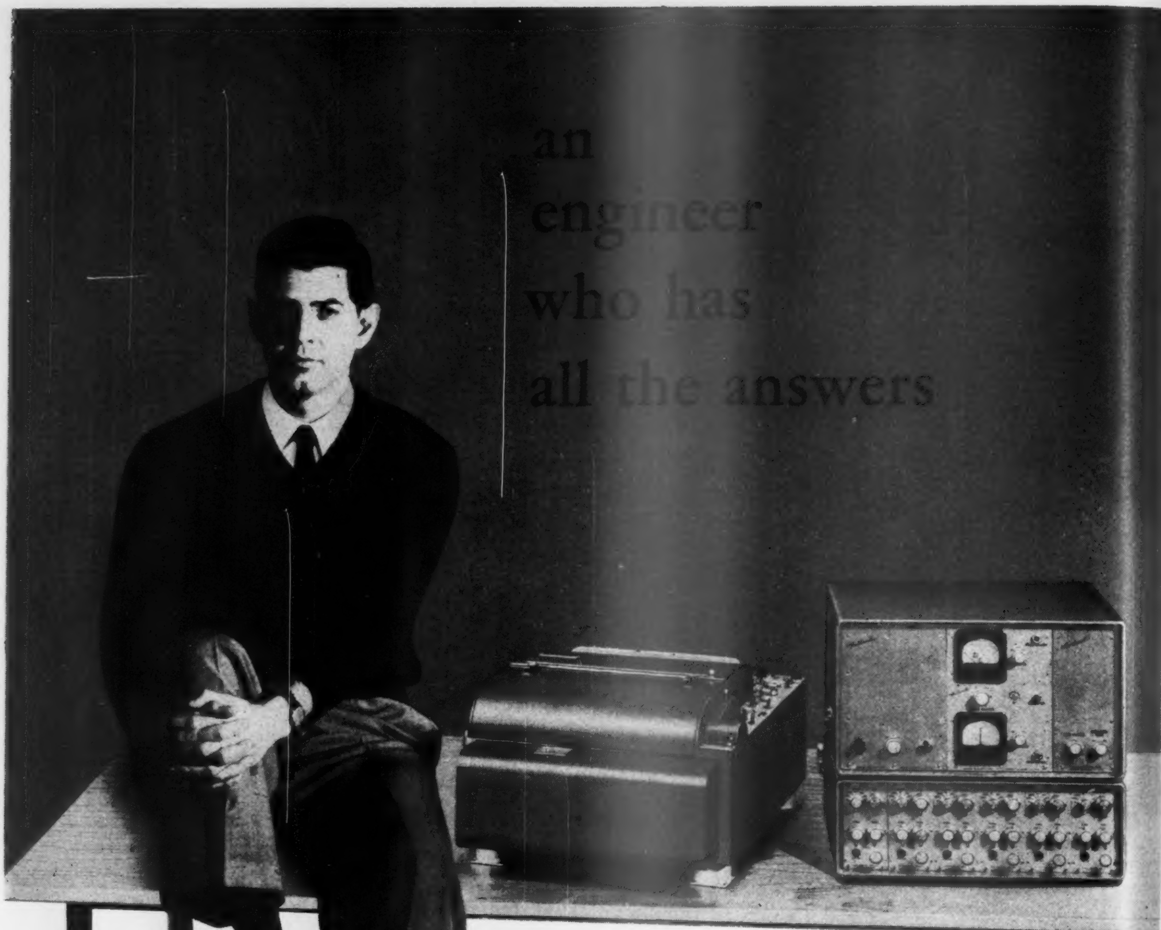

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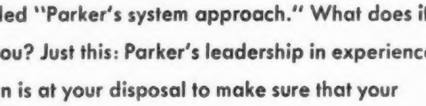

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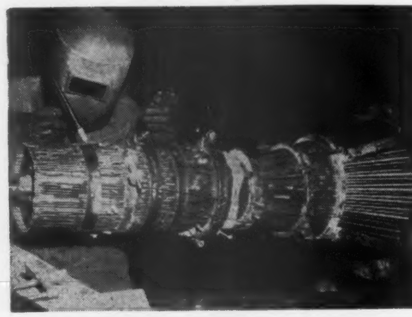

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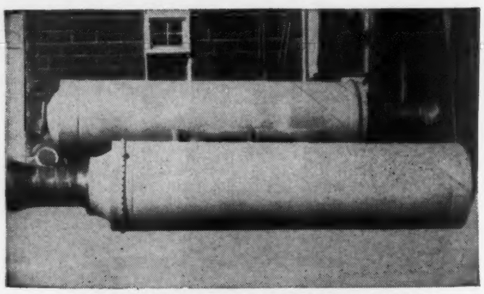

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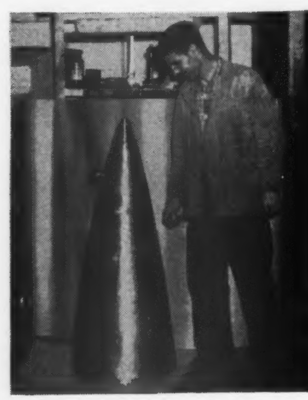
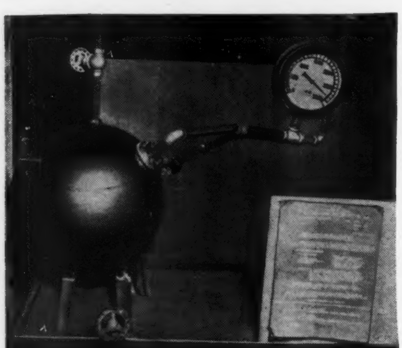


MOCK UP OR COMPLETE MODELS



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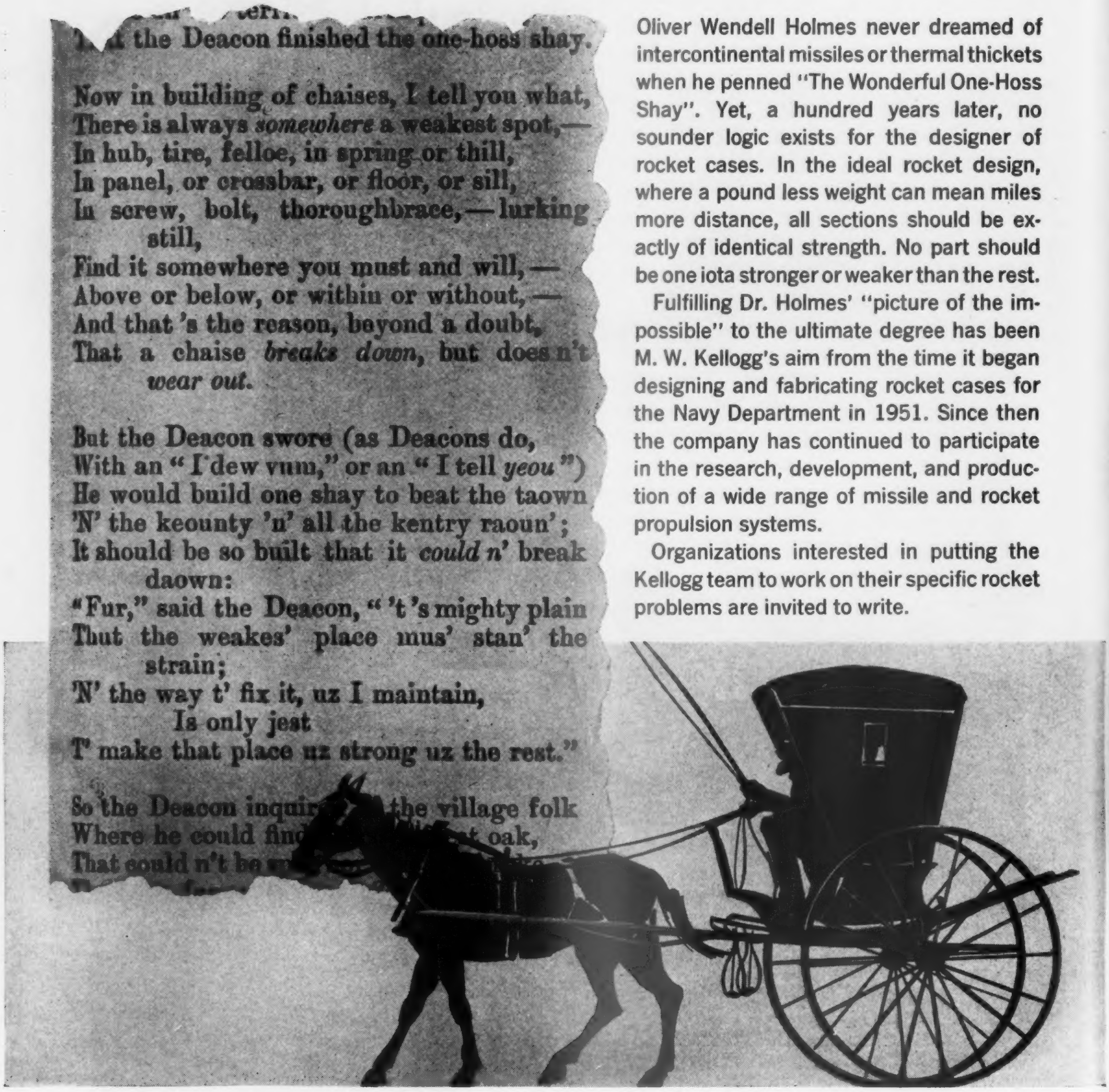
Rocket Logic in Retrospect


the Deacon finished the one-hoss shay.

Now in building of chaises, I tell you what,
There is always *somewhere* a weakest spot,—
In hub, tire, felloe, in spring or thill,
In panel, or crossbar, or floor, or sill,
In screw, bolt, thoroughbrace,—lurking
still,
Find it somewhere you must and will,—
Above or below, or within or without,—
And that 's the reason, beyond a doubt,
That a chaise *breaks down*, but does n't
wear out.

But the Deacon swore (as Deacons do,
With an "I dew vum," or an "I tell *yeou*")
He would build one shay to beat the taown
'N' the keounty 'n' all the kentry raoun';
It should be so built that it *could n'* break
daown:
"Fur," said the Deacon, "'t 's mighty plain
Thut the weakes' place mus' stan' the
strain;
'N' the way t' fix it, uz I maintain,
Is only jest
T' make that place uz strong uz the rest."

So the Deacon inquir the village folk
Where he could find oak,
That could n't be

Oliver Wendell Holmes never dreamed of intercontinental missiles or thermal thickets when he penned "The Wonderful One-Hoss Shay". Yet, a hundred years later, no sounder logic exists for the designer of rocket cases. In the ideal rocket design, where a pound less weight can mean miles more distance, all sections should be exactly of identical strength. No part should be one iota stronger or weaker than the rest.

Fulfilling Dr. Holmes' "picture of the impossible" to the ultimate degree has been M. W. Kellogg's aim from the time it began designing and fabricating rocket cases for the Navy Department in 1951. Since then the company has continued to participate in the research, development, and production of a wide range of missile and rocket propulsion systems.

Organizations interested in putting the Kellogg team to work on their specific rocket problems are invited to write.

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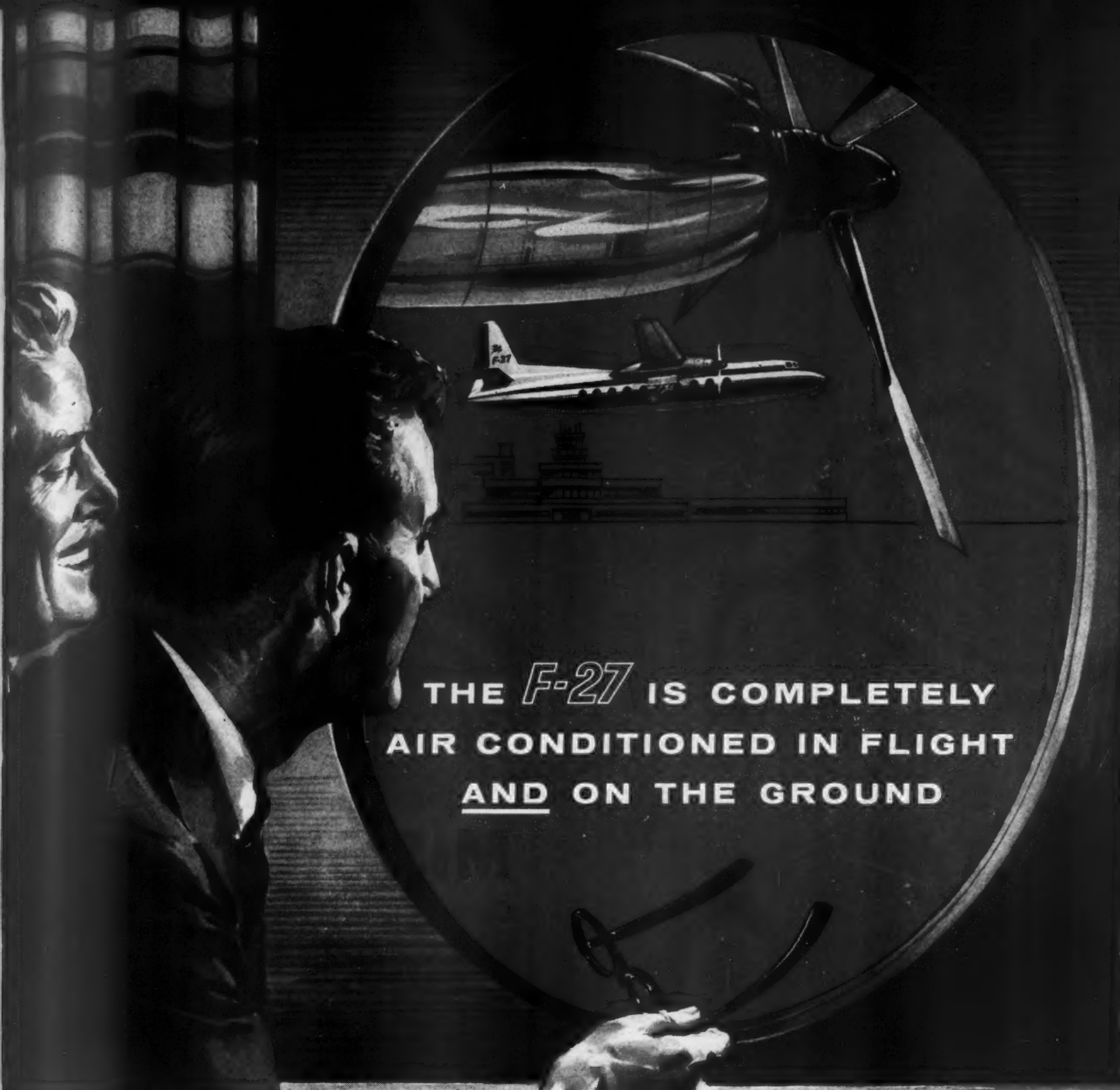

Now the air traveller on a regional route and the executive in a business aircraft can enjoy air-conditioned comfort unsurpassed by any transportation medium. In flight or on the ground, he will be kept comfortably cool if he's in a Fairchild F-27. The F-27 has air conditioning—and pressurization—equalled only by the most luxurious transcontinental and intercontinental airliners.

For the F-27, Fairchild's Stratos Division has developed a new Freon refrigeration system which continues to cool the aircraft even when it stands on the airport with the engines shut down. No ground service, other than electrical power, is necessary. The air conditioning and pressurization system—for which Stratos has full design responsibility—will provide a comfortable cabin under any conditions, from a sun-baked Las Vegas airport to the cold of a Quebec winter.

The Heli-Rotor Compressor for the F-27's Freon refrigerator system.

STRATOS

A DIVISION OF FAIRCHILD ENGINE AND AIRPLANE CORPORATION

Main Plant: Bay Shore, L. I., N. Y.
Western Branch: 1800 Rosecrans Avenue, Manhattan Beach, Calif.

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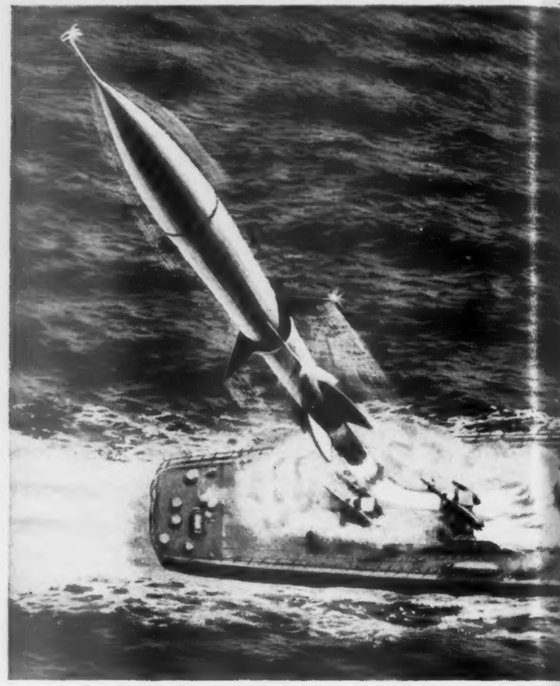

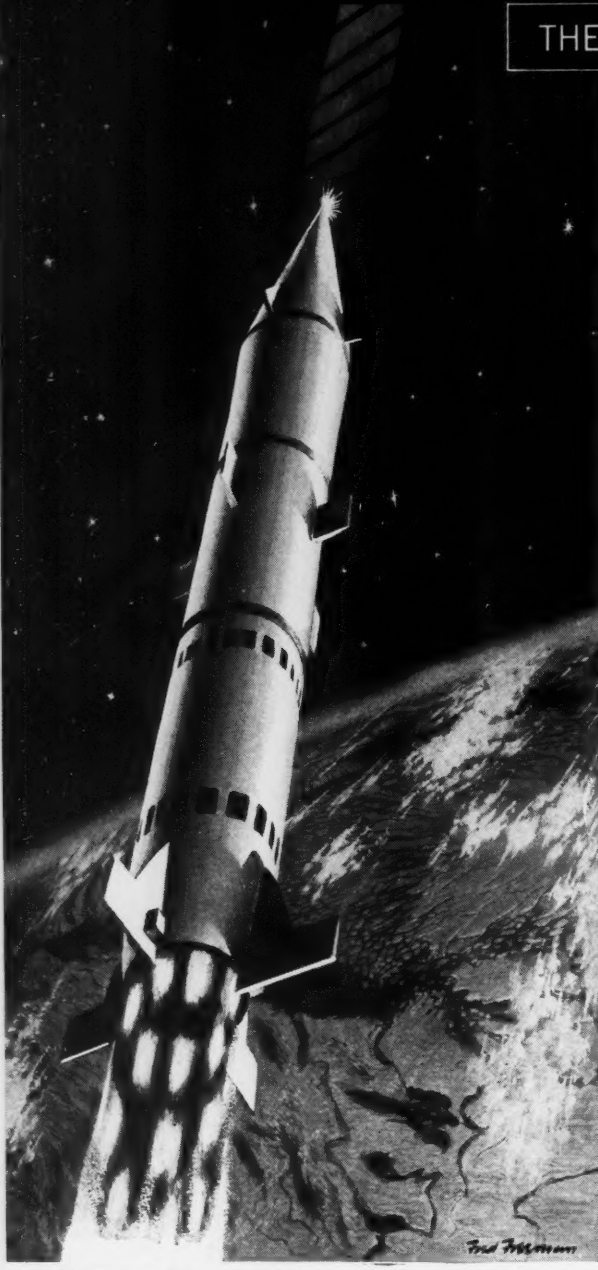

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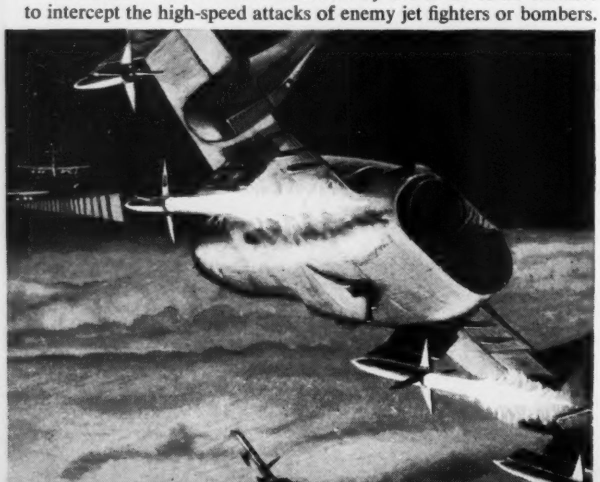

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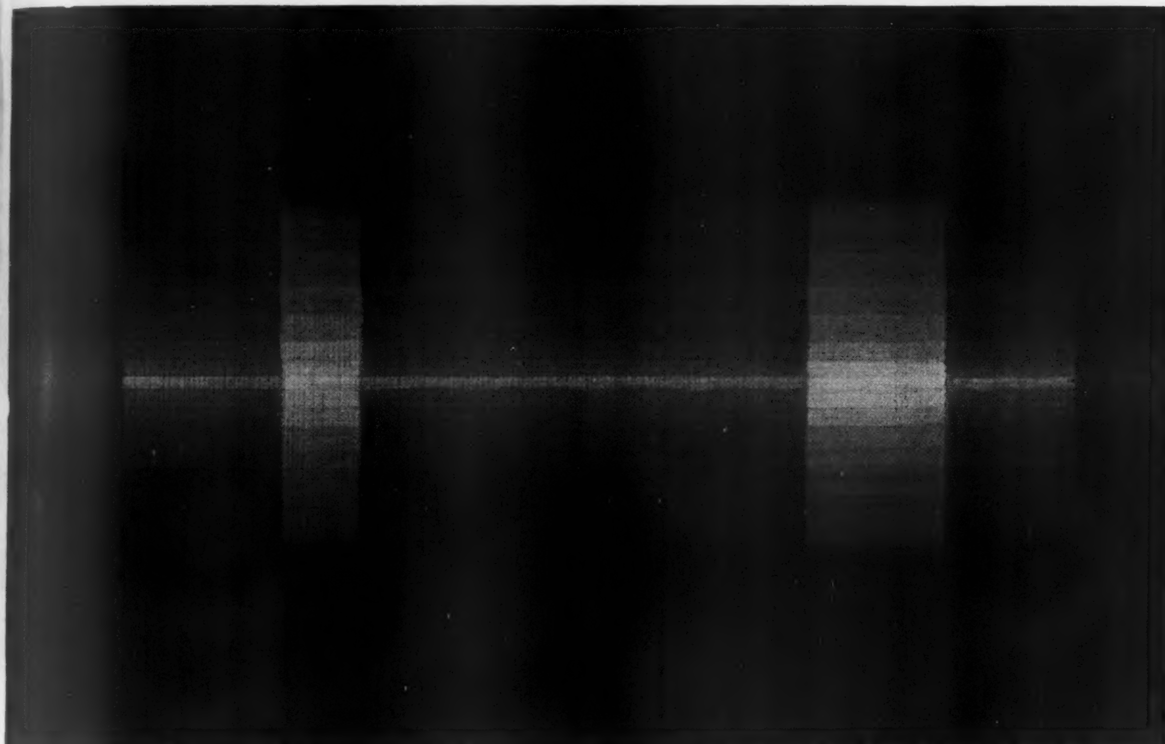

"STUDY FOR ECLIPSE," a preliminary development by the creative team of Simpson-Middleman, artists whose work is a penetrating expression of the forces and phenomena of the natural sciences. This painting is one of the steps—ground structure—in which the ultimate action will take place. Courtesy of John Heller Gallery, Inc.

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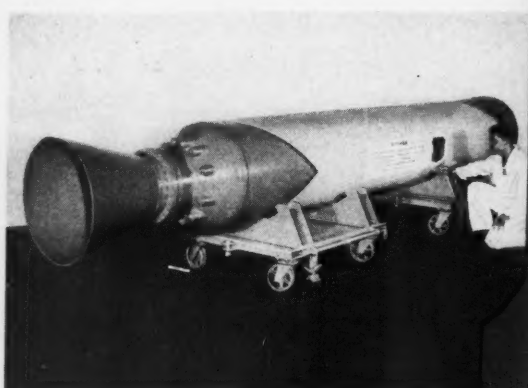

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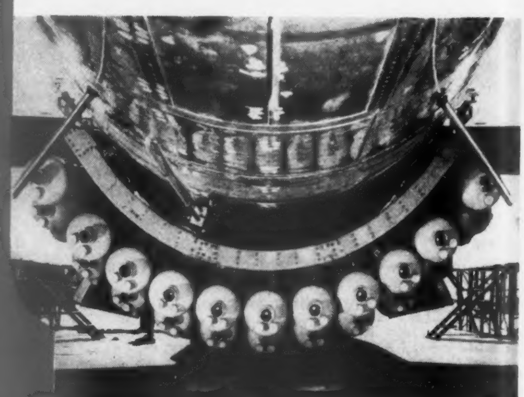

The M15 JATO loaded on Boeing B-47. The first JATO to meet rigid Air Force performance tests. (Boeing Airplane Company photo.)

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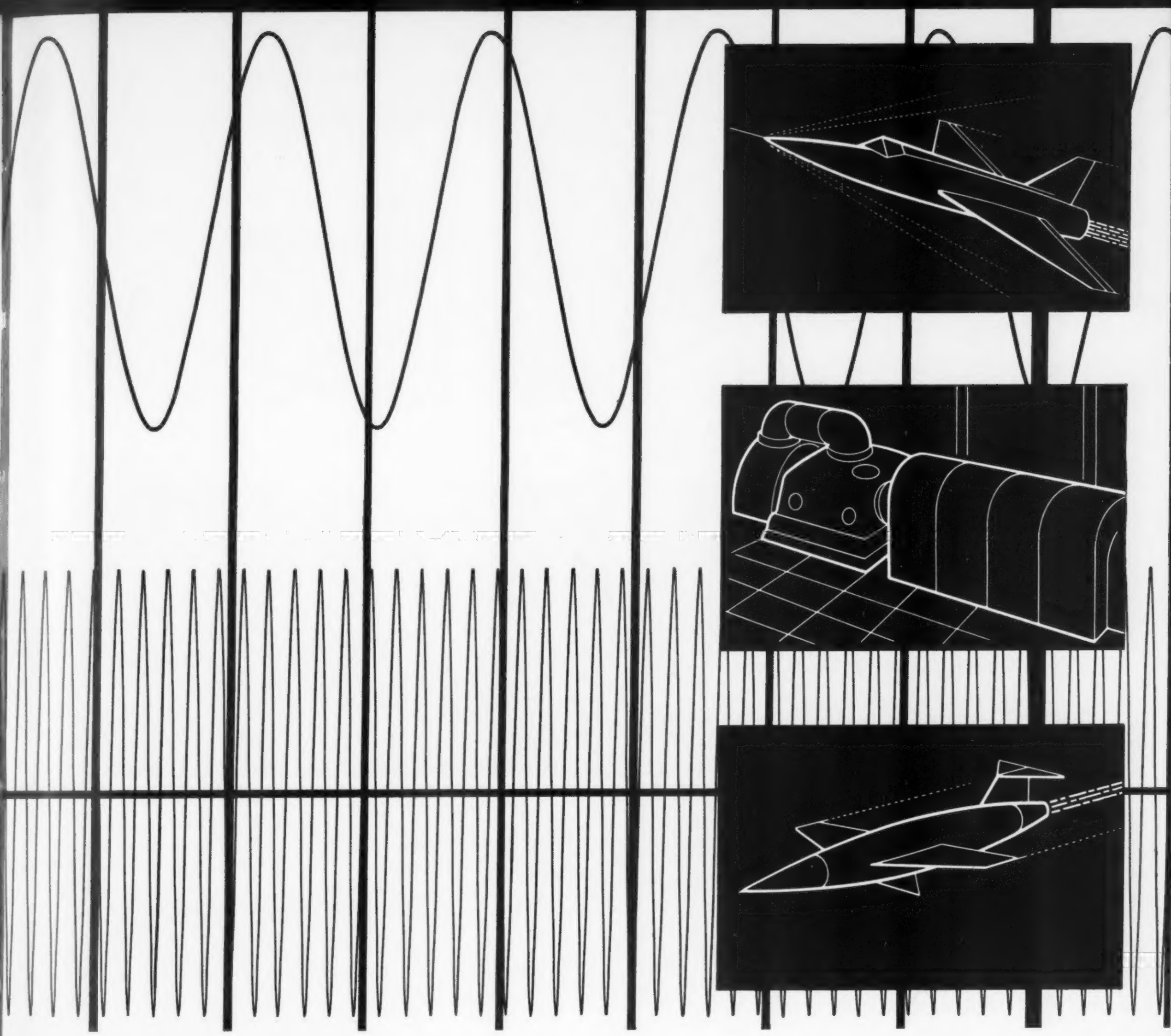

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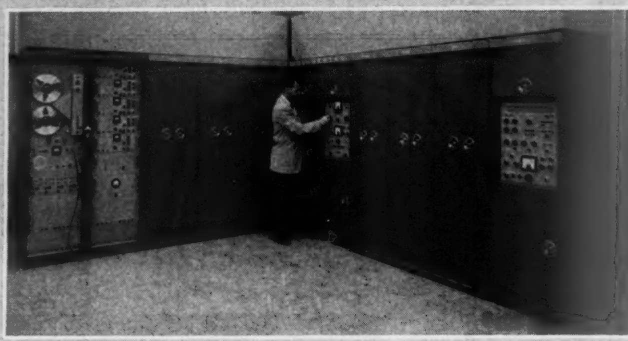

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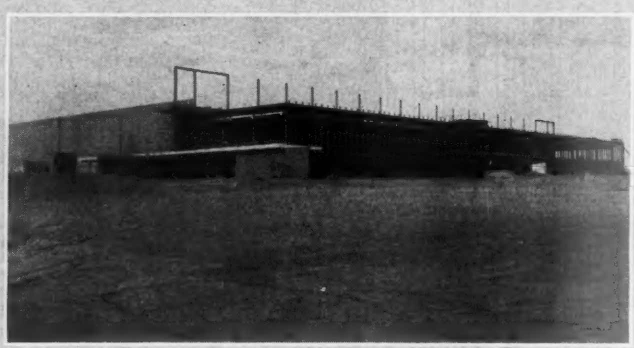
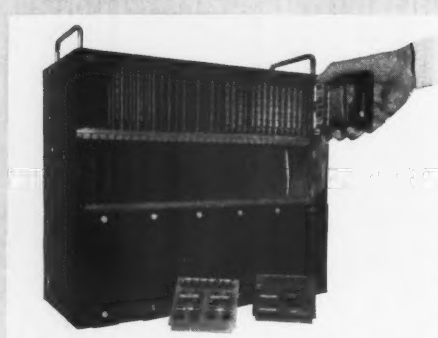


First unit of Denver manufacturing plant now nearing completion



Input-output unit of the Ramo-Wooldridge RW-30 airborne digital computer

Pictorial **PROGRESS REPORT**

The photographs above illustrate some of the recent developments at Ramo-Wooldridge, both in facilities and in products. Work is in progress on a wide variety of projects, and positions are available for scientists and engineers in the following fields of current activity:

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JET PROPULSION
A publication of the
AMERICAN ROCKET SOCIETY
Research and Development

VOLUME 27 NUMBER 9

TRACK AND SLED DESIGN

Supersonic Track Facilities at the Naval Ordnance Test Station

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U. S. Naval Ordnance Test Station, China Lake, Calif.

Introduction

FOR many years, the problem of equipment function under conditions of high speed and acceleration has been of extreme interest to designers of aircraft and weapons systems.

The need stems in part from the fact that in spite of our research ability and technical know-how there are certain scientific phenomena which cannot be accurately predicted under changing environmental conditions. It is especially important in the weapons industry to make adequate dynamic tests to prove out new design.

During and following World War II, scientists and engineers at the U. S. Naval Ordnance Test Station sought better ways of testing rockets and guided missiles. The need soon became apparent for a moving target whose position could be predicted at any given time, and could be closely controlled with respect to the position of the firing aircraft. The second need was to check aircraft rocket launchers under simulated flight conditions without endangering either the aircraft or the pilot.

At a site on this station a railroad track was laid in 1946, and various means of propulsion were attempted. The first successful track runs were made using a sled powered by a gasoline railroad car.

The need for higher speed and acceleration was soon apparent. Rocket propulsion of the sled became successful when the wheels were replaced by slippers with bearing surfaces which gripped the rail head on all sides. This was the real birth of track testing.

Supersonic Tracks

B-4 Track

The original moving target track at the NOTS has been extended and improved so that it is now capable of carrying relatively light sleds traveling at speeds up to 1300 mph. This track, now designated as B-4, is 14,500 ft long (Fig. 1). The standard gage rails are welded for the first 10,500 ft to eliminate splice bars at the rail joints. Sand piled between the rails is used to stop sleds on the track. B-4 is used regularly for testing guided missile components, such as fuses, warheads, guidance and control devices and aircraft missile launchers.

SNORT

The Naval Ordnance Test Station early recognized the need for a facility engineered to cope with the more complex problems of full scale captive testing of aircraft, guided missiles and aircraft and missile components. As a result, with Bureau of Ordnance and Department of Defense approval, the Supersonic Naval Ordnance Research Track (SNORT) planning group was established in 1950 to design a facility for sled velocities on the order of 0 to 3500 fps. To accomplish such work, it was first necessary to build a foundation for the track capable of withstanding the anticipated loads and to hold the track in precision alignment. SNORT is 21,500 ft long (Figs. 2 and 3). It consists of a two-rail system of standard gage using 171 lb Bethlehem crane rail with dowel jointed ends precisely aligned. The last 10,000 ft of the trough is equipped with a recirculating water system, fed from a well and reservoir, which provides the means of bringing high speed carriages to a stop. Two conventional types of water brakes, probe and horizontal momentum exchange, are used. The first firing was conducted on SNORT in Nov. 1953.

Since then the facility has gained recognition in such fields as escape systems testing, aerodynamic flutter testing, armament compatability testing, inertial guidance components and other fields of environmental testing. Each day new and different techniques are proposed and attempted. Here, for the first time, a full-scale aircraft section may be brought up to speeds much greater than Mach 1, sustained at that speed for

Fig. 1 View toward muzzle of B-4 14,500-ft-long track

Presented at the ARS Spring Meeting, Washington, D. C., April 4–6, 1957.

[1] Head, Track Projects Branch.

[2] Mechanical Engineer. Mem. ARS.

Fig. 2 Aerial view of SNORT and headquarters area

Fig. 4 Breech end of the 3000-ft G-4 track

Fig. 3 Breech end of SNORT—a liquid fuel rocket sled is being prepared for a firing

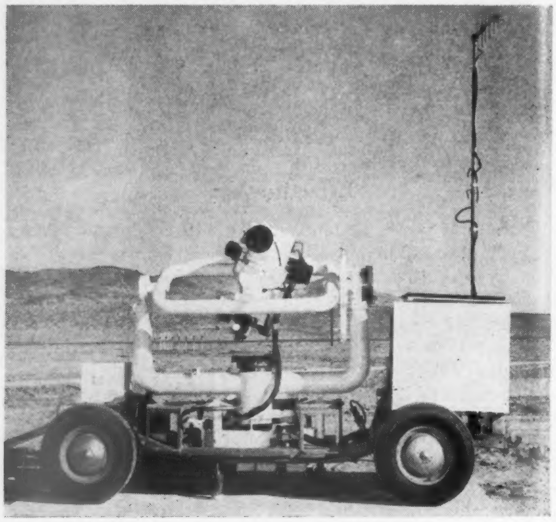


Fig. 5 A CZR Bowen camera set up in the field on a permanent pad

the time necessary to make observations and sample data, and stopped intact—available for the most important part of any test, the post-mortem.

G-4 Track

To meet additional requirements and provide for a well-integrated track test facility at this station, the G-4 track was constructed in 1954 (Fig. 4). The track is 3000 ft long and has pressure-welded 171-lb crane rails. The gage is $33\frac{7}{8}$ in. The muzzle of this track overlooks a 500-ft declivity. Rockets and missiles are accelerated on the track to realistic launching velocities, then fired into space, i.e., warhead and fuse functioning under free flight conditions can be tested. Warheads of large missiles have been accelerated up to 2000 fps.

Track Instrumentation

Telemetry

Most of the functional data obtained from sled-borne equipment is telemetered to a ground station. At SNORT for example, four FM/FM carriers can be received and the subcarrier signals recorded on magnetic tape.

Photographic

Photographic instrumentation is divided into two general types—ground and sled-borne. The work horse of the photographic ground instrumentation is the Bowen frame camera (CZR) used for the recording of position, velocity and acceleration of track test vehicles and the rockets, missiles or other objects which may be launched or ejected from the vehicle during the test (Fig. 5).

The Mitchell Chronograph, mounted on a M-45 tracking mount and operating at frame rates of from 20 to 120 frames/sec, depending upon the requirements of the test, is used extensively at the station to provide data such as attitude, deflection, pitch, yaw and roll. They are frequently mounted on an over-track bridge to provide deflection data on ejected items, such as seats, dummies, capsules, etc.

Detailed studies from the ground are provided by high

frame rate cameras, such as the Eastman, and the Wollensak Fastax prism cameras. These cameras provide data at recording frequencies of from 500 frames to 16,000 frames/sec.

The increasing variety of tests conducted on the high speed tracks has resulted in a much greater need for photographic data recorded on the test vehicle itself. The Wollensak Fastax camera, which has been modified and supported by a special mount for operation at accelerations over 60 g has been applied to most of the tests requiring sled-borne photographic recording. One pin-registered camera, the Photo-Sonic Track Sled Recorder, 35 mm ½ frame, provides data up to 200 frames/sec, and is designed to operate under accelerations up to 50 g.

The control of sled-borne camera equipment is accomplished by the use of charged screen boxes mounted along the track beam, sled-mounted knife blades and sled-borne pistol switch assemblies. The firing of the squib forces a piston which in turn controls switches in the camera control circuits.

Carriage Design

The carriages required to transport the test objects are just as important as the high speed tracks. The carriage or sled designer is faced with a multitude of conflicting requirements which must be resolved in an optimum manner. For example, weight and drag must be balanced by adding thrust, but adding thrust also increases the weight. One may find eventually that adding an additional rocket to the sled will actually decrease the maximum velocity.

The carriage design is usually based on three phases: (a) Acceleration, (b) sustain and (c) braking. Economic factors such as propellant cost vs. performance must also be evaluated.

More complete carriage design details may be found in the Appendix.

Sled Position vs. Time

The basic measuring system, used at the station, to determine sled position, consists of a permanent magnet mounted on the sled with pick-up coils located at 100-ft intervals throughout the length of the track. Transmission lines connect the track coils to the terminal equipment (pulse shaper, timer and recorder) in the test control building. This system gives velocity of the sled averaged over 100-ft intervals to an accuracy of about 0.1 per cent. Many tests, such as inertial guidance system tests, require more precise measurement of velocity over a relatively wide frequency bandwidth. To meet this need, the station has developed a system for SNORT to determine velocity to 1/20,000. This system is based on a method proposed by Beutler and Rauch.[3]

It consists, briefly, of using the track coil system plus a sled-borne accelerometer. The accelerometer and track coil data are combined so as to obtain optimum velocity information with minimum error. The track coil pulses and telemetered accelerometer data are recorded on a magnetic tape along with a time base. The tape is played back through an analog-to-digital converter producing an output tape which is suitable for entry into an IBM 701 computer. The velocity data from the IBM 701 is put out in plotted or tabular form and on tape for further computational processes if necessary.[4]

Typical Track Tests

Fig. 6 shows a sled ready for an emergency escape test on SNORT. This is a forward section of a high speed navy fighter aircraft. The operation of the escape system was

[3] Beutler, F. J., and Rauch, L. L., "Velocity Measurement for Rocket Sled Testing," The Ramo-Wooldridge Corp., Los Angeles, Calif., Memorandum, Sept. 19, 1955.

[4] "A Precision Velocity Measurement System for SNORT," Staff Test Dept., U. S. Naval Ordnance Test Station, NAVORD Report 5247, April 1, 1956.

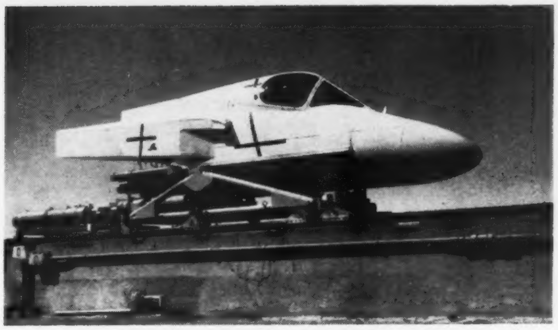


Fig. 6 The forward section of a navy fighter plane ready for a seat ejection test on SNORT

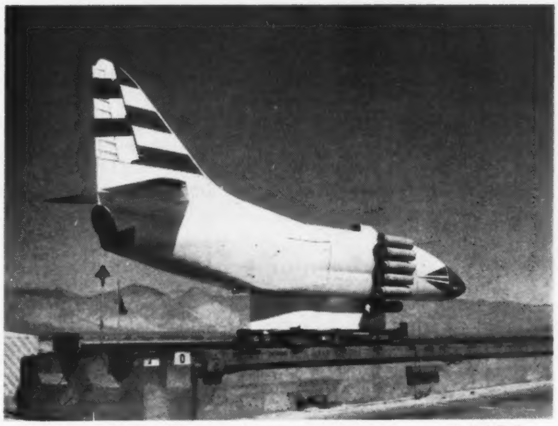


Fig. 7 Test vehicle ready for tail flutter test on SNORT

Fig. 8 Blast damage from high explosives on an aircraft wing after run on SNORT

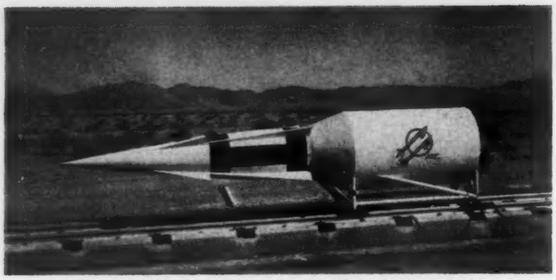


Fig. 9 Missile warhead test sled on G-4 track

tested under simulated flight conditions at velocities up to 600 knots.

The tracks are widely used to check aerodynamic flutter of aircraft control surfaces. A sled for testing flutter characteristics of the tail assembly of a navy fighter plane is shown in Fig. 7.

The sled in Fig. 8 was used to study the effects of blast from high explosive charges on a moving aircraft target. Extra sets of slippers were used to absorb the high loads produced by the blast.

Fig. 9 shows a missile warhead mounted on a test sled on the G-4 track. The purpose of this test was to study the effects of motion on the warhead performance. The warhead was detonated when the sled reached the speed comparable to that of the missile in free flight.

Summary

A total of nearly 500 test runs were made on the supersonic tracks at NOTS during the calendar year 1956, an increase of 63 per cent over the number of runs conducted in 1955.

The high speed track has demonstrated its usefulness as a tool to further knowledge in many scientific fields. It has taken its place along with the wind tunnel, centrifuge, shake table and engine test stand. The U. S. Naval Ordnance Test Station has been developing and operating track testing facilities for over 10 years. Here we have an integrated facility which has three versatile high speed tracks with supporting services in engineering design, project engineering and coordination, instrumentation engineering and operational engineering.

Research and development work in sled design, sliding friction, instrumentation, track vibration and others is proceeding to further improve our capabilities and techniques.

APPENDIX

SNORT Carriage Design

Introduction

The main problem of rocket-propelled sled design is that of attaining the velocities required although additional requirements, such as stopping the sled on the track and providing for a sustained velocity or a programmed acceleration, may complicate the problem.

Due to the cost of the propellants used and the cost of the sled itself, the design problem is reduced to finding the sled-propellant system which will be the lowest in price but yet do the job for which it was designed. A cost study of the type shown in Fig. 10 in combination with the design decides the propellants used and the type of sled designed.

Features of the Design Problem

For convenience, the design problem is often split up into three phases:

The acceleration phase occurs while the motors are accelerating the vehicle up to peak velocity. The acceleration phase may be caused by several motors firing together or in sequence or may consist of one or more detachable boosters accelerating the main vehicle.

The sustain phase occurs when the rocket motor thrust equals the aerodynamic drag of the vehicle. Due to high aerodynamic drag it is usually necessary to provide considerable thrust so that a condition of zero acceleration can be approximated.

In *the braking phase* the carriage is stopped by the action of aerodynamic drag, water braking force and track sliding friction. Accurate evaluation of these three forces is often necessary in the design in order to meet test requirements.

Design for Acceleration and Sustain Phases

Since the main problem consists of reaching a peak velocity, the first step is that of selecting a suitable sled-propellant combination which will yield this peak velocity. A useful and recommended procedure consists of utilizing an approximate vacuum velocity equation as follows:

$$V = \frac{I_t g}{W_{\text{avet}}}$$

V = peak vacuum velocity, fps
I_t = total impulse, lb-sec
g = 32.2 fps^2
W_{avet} = average carriage weight (half burnt weight)

$$I_t = nI$$

n = number of motors
I = impulse per motor, lb-sec
W_{ave} = average motor weight (half burnt weight)
W_{TI} = weight of test item, lb
W_{STI} = weight of structure to support test item, lb
θ = sled structure weight per motor—"growth factor," lb per motor

$$W_{\text{avet}} = W_{TI} + W_{STI} + nW_{\text{ave}} + n\theta$$

$$V = \frac{nIg}{W_{TI} + W_{STI} + nW_{\text{ave}} + n\theta}$$

$$V = \frac{Ig}{W_{\text{ave}} + \theta + \left(\dfrac{W_{TI} + W_{STI}}{n}\right)}$$

By plotting V vs. the number of motors N, a curve such as that shown in Fig. 11 results.

It is believed that the weight estimating procedure used in the vacuum velocity design equation represents a rational

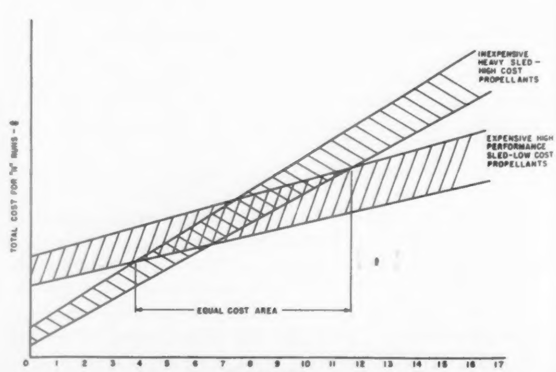


Fig. 10 Type of design as decided by required number of runs

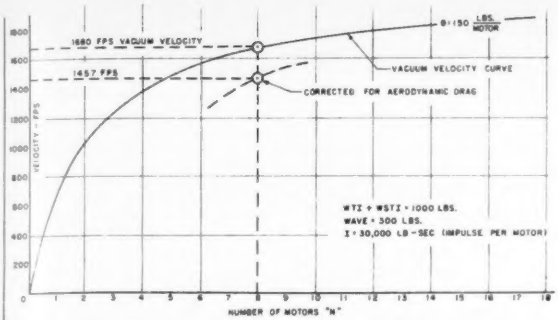


Fig. 11 **Correction of vacuum velocity for aerodynamic drag**

approach to this problem. For the usual SNORT sled, W_{ST} is often about equal to W_{TI}. The "growth factor" θ, which is defined as the weight of sled structure per motor, is a reasonable concept since each motor will require structure to transmit its thrust to the test item and to support the motor against horizontal and vertical loads.

In order to enable the designer to estimate a value for θ, a number of existing carriages were analyzed and a dimensionless weight factor K derived. This parameter K (see Fig. 12) takes account of the fact that sometimes the motor case can be used as part of the stress carrying structure. It also accounts for the fact that the structure weight per motor is a function of the thrust since this structure is used to transmit the thrust. The carriages considered in this analysis (see Fig. 12) run, in order, from heavy inexpensive steel pipe construction to faired aluminum stressed skin construction. The fact that as performance increases weight decreases is clearly seen.

Velocity Reduction Due to Aerodynamic Drag

Unfortunately in the design equations considered so far, no correction has been made for aerodynamic drag. Therefore, after selecting the number of motors needed from the V vs. N plot, the designer takes the test item, the N motors, the skids, and makes a series of layouts showing various arrangements of test items, motors, skids, water brakes, etc.

Upon selecting the most likely configuration, the aerodynamic drag at peak velocity is computed. By doing this, the designer is able to make such a simple check as determining whether the drag exceeds the thrust at peak velocity. Also if a sustain phase is desired, the sustainer requirements can be estimated and the weight added into the carriage weight, for correction of V vs. N plot. For this peak drag calculation, past experience at NOTS has demonstrated that it is possible to predict the drag to within ± 30 per cent.

The next step after computing the peak velocity drag is to calculate the velocity reduction caused by aerodynamic drag. Due to the "second order" effect of the drag correction, certain simplifying approximations can be easily made. The first assumption is that the drag is linear with velocity between 700 fps and the peak velocity. (Justification of this assumption will be given later.) The derivative of a simple velocity correction formula is then possible.

$$m \frac{d^2x}{dt^2} = \Sigma F$$

$$m \frac{d^2x}{dt^2} = T - C_D A \rho \frac{V^2}{2}$$

$$m \frac{d^2x}{dt^2} = T - \frac{C_D A \rho}{2} \left(\frac{dx}{dt}\right)^2$$

m = average mass of carriage, slugs
T = thrust, lb
C_D = drag coefficient
A = drag reference area, ft²
ρ = mass density of air, slugs/ft³
V = velocity, fps

Approximate Drag by Straight Line:

$$C_D \frac{A\rho}{2} \left(\frac{dx}{dt}\right)^2 = NV + P = N \frac{dx}{dt} + P \text{ (see Fig. 15)}$$

$$m \frac{d^2x}{dt^2} + N \frac{dx}{dt} = T - P \qquad \text{or} \qquad m \frac{dv}{dt} + NV = T - P$$

Solve This with Following Boundary Conditions: when $t = 0$, $V = V_0$; when $t = t$, $V = V$.

$$V = \frac{T - P}{N} \left(1 - e^{-\frac{Nt}{m}}\right) + V_0 e^{\frac{-Nt}{m}}$$

Upon plotting the corrected velocity on the V vs. N plot, Fig. 11, one can see the effect air drag has on peak velocity. By noting the difference between the two velocities one can estimate possible increases of velocity by streamlining and can re-evaluate the propulsion system. By repeating this procedure until a satisfactory velocity is obtained, an optimum configuration and propellant system can usually be arrived at. The air drag velocity equation can also be solved for the "boost velocity" V_0 if a booster is to be used.

Discussion of Aerodynamic Drag Prediction

The importance of synthesizing an accurate drag curve during design of a supersonic carriage cannot be overemphasized. In the past a tendency on the part of the designer to underestimate the drag of a carriage has been noted. If the drag is underestimated, the motor requirements will be underestimated and the magnitude of the stopping problem will appear greater.

Fig. 13 shows a series of curves which plot C_D vs. Mach number. The range of reasonable C_D values probably lies between that of the cone cylinder and that of the flat noted cylinder. The major difficulty with applying these curves to carriage drag prediction is that an actual carriage is composed of many elements: Cones, wedges, cylinders, flat plates, base drag, skin friction and interference drag. Procedure used at NOTS is that each element is handled as a separate part and the C_D of each part is multiplied by the area A of that part and the C_DA are totaled to give a C_DA for the complete carriage. An example is given in Fig. 14 which illustrates an "aerodynamically clean" carriage. It should be noted, for

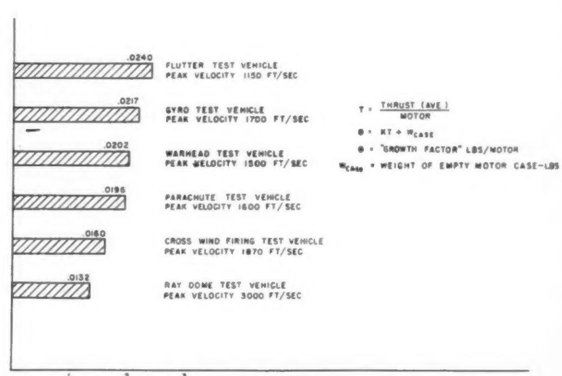


Fig. 12 Sled structure and motor case weight per pound of motor thrust

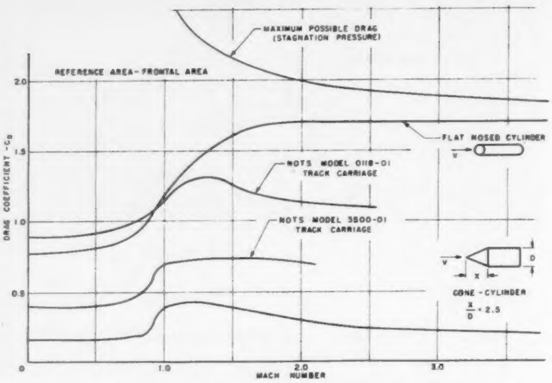


Fig. 13 Sled aerodynamic drag coefficients limitations

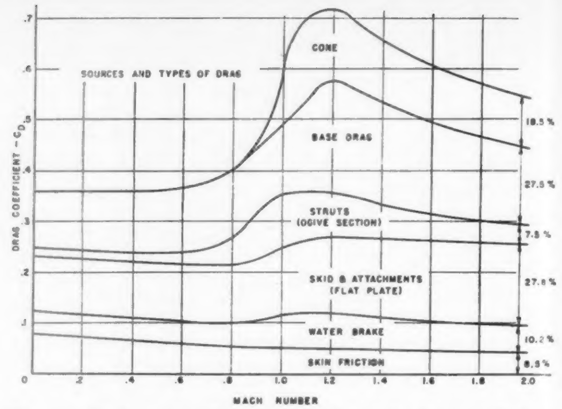


Fig. 14 Rocket propelled sled aerodynamic drag coefficients

this "aerodynamically clean" carriage, that over half the drag is composed of attachments to the basic cone cylinder carriage body.

Experience at NOTS has indicated that it is possible to build up a drag curve which will be accurate within ± 30 per cent (with the supersonic part being more accurate than the subsonic portion). A plot of drag vs. velocity is given in Fig. 15. This plot is based on drag of the NOTS Model 3500-01 track carriage. Skid friction is included in this plot and, as can be seen, is a very small part of the total drag. Fig. 15 is the curve which was used for the previous V vs. N plot drag correction and it is seen that the straight line approximation from 700 fps is justified, particularly since the drag curve is only accurate to ± 30 per cent.

Braking Phase

The problem of stopping a carriage on the track can quite often be accomplished on SNORT by the combination of air drag and track friction. If one depends on this type of braking it is desirable to have estimated correctly the air drag. If the air drag is underestimated the carriage will appear to coast too far and a water brake will appear to be necessary. Due to the possible 30 per cent error in the theoretical drag curve, usually the drag is lowered by 30 per cent in estimating the coast distance so as to give a conservative coast distance.

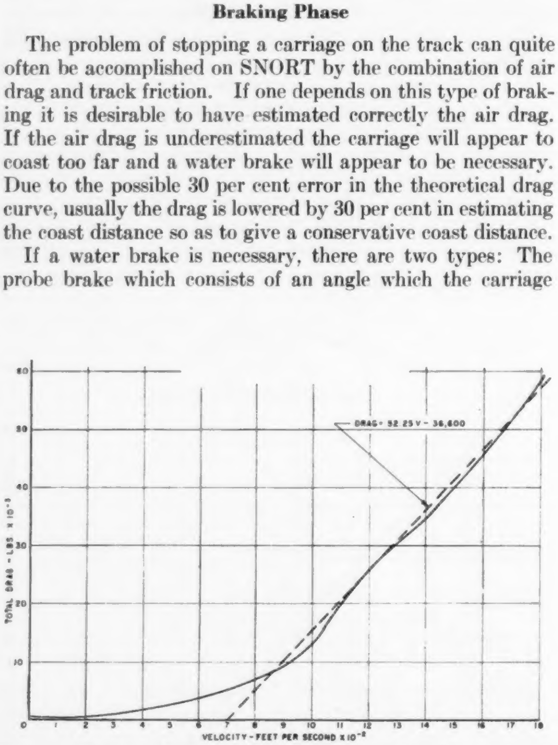
If a water brake is necessary, there are two types: The probe brake which consists of an angle which the carriage drags through the water, and the momentum exchange brake. The probe brake is generally not used on large carriages or for deceleration exceeding 5 g because of the structural problems associated with transmitting the braking force into the carriage.

The momentum exchange brake has been more highly developed than the probe brake and is generally considered to be the high performance brake. The design of a brake for a given carriage system is a problem in itself; however, practically any deceleration can be obtained. The limited experience with the momentum exchange water brake indicates that a deceleration can be easily predicted and held within about ± 20 per cent.

The complexity of the braking phase can be seen from an inspection of the equations of motion which describes the braking phase.

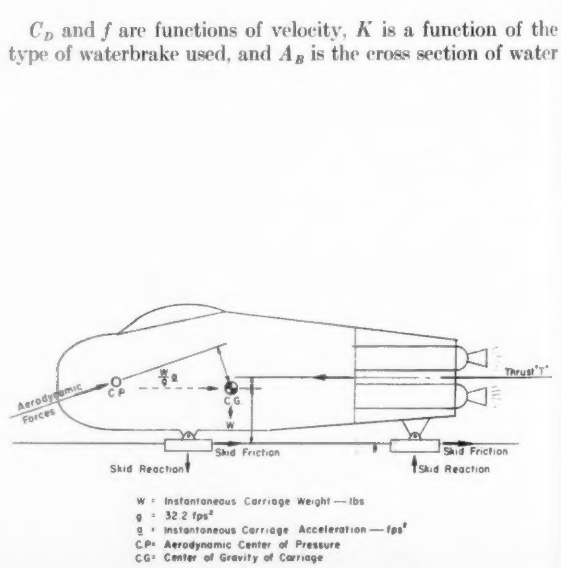
$$\underbrace{m\frac{d^2x}{dt^2}}_{\substack{\text{carriage}\\ \text{deceleration}\\ \text{term}}} + \underbrace{\frac{C_D A \rho}{2}\left(\frac{dx}{dt}\right)^2}_{\substack{\text{air}\\ \text{drag}}} + \underbrace{K A_B \left(\frac{dx}{dt}\right)^2}_{\substack{\text{water}\\ \text{brake}}} + \underbrace{wf}_{\substack{\text{skid}\\ \text{friction}}} = 0$$

C_D and f are functions of velocity, K is a function of the type of waterbrake used, and A_B is the cross section of water



Drag = $NV + P$ = 52.25V-36,600; N = slope of linear drag appoximation; P = intercept of linear drag approximation on drag axis

Fig. 15 Typical drag curve—justification of straight line approximation



W = Instantaneous Carriage Weight — lbs
g = 32.2 fps²
$\underline{a}$ = Instantaneous Carriage Acceleration — fps²
C.P= Aerodynamic Center of Pressure
CG= Center of Gravity of Carriage

Fig. 16 Forces acting on carriage

picked up by the water brake entrance section and is a function of the distance X traveled down the track. Useful approximate solutions to this equation have been developed.[5] It is desirable to consult with NOTS before a water brake is designed. At present the NOTS is engaged in a theoretical and experimental study of the water braking problem.

The track friction term f is never greater than 0.35 and for velocities over 150 fps is constant at about 0.11 to 0.15. Although track friction is the force that finally stops the carriage, for velocities above 200 fps the track friction term can be neglected.

Structural Design

The art of SNORT carriage design has progressed to the point where it is possible to successfully design using a safety factor of 1.5 (based on yield strength). The necessity for this low factor of safety is, of course, dictated by the desire to keep the sled structural weight as low as possible so as to minimize propellant requirements.

Freebody Diagram in Design

The key to successful SNORT carriage design lies in the correct application of the "free body" diagram (Fig. 16). The forces acting on a carriage are the thrust vector, aerodynamic drag and lift vectors, and the inertia of the carriage acting through its center of gravity. Since the externally applied forces almost never pass through the center of gravity, reactions on the carriage skids results.

Skid Wear Often Critical

If reactions on the skids result in a nominal bearing load on the skid plates greater than 260 psi, a problem must be expected. Consequently, it is desirable to attempt to reduce skid reactions by designing so that the thrust and drag vectors pass through, or at least close to, the carriage center of gravity. However, additional skids can be added if skid reactions cannot be kept down. The rail itself can withstand a maximum load (upload) of 37,000 lb. The heavy duty skids available at NOTS can withstand an 8000 lb-upload (260 psi, bearing load) before wearing dangerously. It is desirable, however, to keep the load application time below 2.0 sec if possible. Studies into skid wear are in progress at NOTS.

Dynamic Design Criteria

In most carriage design, the rocket motors used have a very sudden thrust build-up (5 to 10 millisec) and hence the thrust constitutes a "suddenly applied load." Therefore, in the design of the structure a factor of 2.0 should be used when computing the reactions just after motor ignition. Since this is a "transient" load, it is not considered when computing skid reaction.

[5] Nelson, D. M., and Ankeney, D. P., U. S. Naval Ordnance Test Station, "Ballistic Formulas for Track Carriages," NOTS, China Lake, Calif., Jan. 24, 1956. (NAVORD Report 4998, NOTS 1330.)

A further dynamic load encountered by the carriage is track induced. Since the track is not perfectly aligned, the skids in traveling over the rail will bounce over local track roughness and cause deflections (and hence stresses) in the carriage. The horizontal and vertical loads induced by track roughness and malalignment are often referred to as "bounce loads" and experience has indicated that the following equivalent values of acceleration applied to the carriage may be used: 2.0 g up to 500 fps, 5.0 g up to 1500 fps and 7.0–10.0 g above 1500 fps. Studies of bounce load are presently in progress.

Combination of Static and Dynamic Loads

As a general rule the bounce loads are superimposed on the "free body" reactions when computing stresses in the carriage structure. However, only the free body reactions are used in computing the bearing load on the skids when checking for the allowable skid "wearing" load. This procedure of ignoring bounce loads in computing wear loads is not very rational but it probably can be excused since it has grown from empirical data derived from cases where skids have worn excessively on actual carriages.

For supersonic carriages the thrust and aerodynamic forces usually are much greater than any other forces and the carriage is primarily stressed for these forces. For the subsonic carriage, bounce loads are usually critical and the design is often decided primarily by this bounce load.

Peak Design Forces

For the average carriage the peak forces (and hence maximum stresses) applied to the carriage may occur at four points during the travel of the carriage down the track: At main carriage motor ignition, at peak motor thrust (usually at midpoint of burning time), at peak velocity (motors about to burn out) and shortly after water brake engagement (peak braking deceleration). It is usually necessary to check the design at these points.

Aerodynamic Loads on Carriage Bottom

One factor peculiar to track testing is the possibility of high aerodynamic lift loads created by aerodynamic "choking" of the duct formed by the carriage bottom and the trough between the rails during transonic velocities. This choking problem can usually be eliminated if the bottom of the carriage is parallel to the trough bottom and the carriage bottom does not extend completely to the rails so as to permit pressures developed to bleed off.

Conclusion

The problem of rocket-propelled carriage design has been briefly discussed with emphasis primarily on the importance of a correct initial design study. Structural criteria have also been discussed, with the major design approach and criteria outlined.

It is hoped that this paper will stimulate criticism and discussion of the approach used in the design of high speed track-borne vehicles.

Aberdeen Proving Ground Ballistic Track

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Aberdeen Proving Ground, Aberdeen, Md.

Introduction

WITH an increasing requirement for the terminal evaluation of rocket warheads and fuses, it was decided that a very long launcher or ballistic track would best fulfill this need.

The Aberdeen track was constructed in 1953, and the first test round fired during the latter part of October 1953. Since this time over 700 test and experimental rounds have been fired, the bulk of test work being on classified rocket warheads and fuses.

Along with test work, firings have been made to reach a higher maximum terminal velocity.

The track is available to all Department of Defense agencies and to organizations developing products related to national defense.

Track Test

For all firings, test items have been propelled by solid propellant rocket motors.

Various combinations of booster motors and boost stages have been used to obtain desired terminal velocities. On lightweight warheads, one rocket motor and one stage have often been sufficient to give desired results. On heavy warheads or light loads at high speeds, multiple motors and two or more stages have been required to obtain desired velocities.

The rocket motor that has been the workhorse for most of these firings has been the Navy 5-in. HVAR. This high velocity aircraft rocket has been suitable as a booster motor for velocities slightly beyond Mach 2. The motor as used without warhead weighs 81 lb, including 25 lb of propellant. This gives a propellant to total weight mass ratio of 31 per cent, which is quite low. However, with the added skid hardware weight of 10 lb, the mass ratio drops to $27\frac{1}{2}$ per cent. In addition to the mass ratio handicap, the motor burns for the relatively long period of 1 sec at 70 F. With a two-stage boost of 2 sec and only 2500 ft of track, it was difficult to exceed 2500 fps and burn all the propellant in each motor.

To meet a test requirement for velocities in excess of Mach 3, it was necessary to find a booster motor that had a higher mass ratio and a shorter burning time. Furtunately, some 3-in. antiaircraft rocket motors were available. These motors had a much higher specific impulse, a higher mass ratio—12 lb of propellant to 18 lb of total weight or 66 per cent, and a shorter burning time—$\frac{3}{4}$ sec at 120 F. On a check run that used two of these motors in the first stage and one motor in the second stage, a velocity of 3925 fps was attained. Had the track been longer, the velocity would have been greater, because only 70 per cent of the energy was used in the first stage. The second stage was burnt out so that the test item would not be under thrust at the end of the track. Consideration is being given to lengthening the track so that higher velocities can be attained.

Supersonic Ballistic Research Track

The ballistic track is a precision aligned research track located at Gunpowder Neck, Aberdeen Proving Ground, Md. (see Fig. 1). The 2448-ft track was built to provide guidance for rockets to reduce the dispersion of rounds during terminal ballistic tests at speeds ranging into the supersonic. It can be used for a variety of testings which require high velocity under conditions simulating free flight, with the advantages of controls approaching laboratory conditions.

Items tested on the track are mounted on metal shoes. The items are accelerated to required velocities by the use of combinations of rocket motors.

Uses

The ballistic track is available for a variety of testings (Fig. 2) which require high velocity, such as:

Aeroballistic Tests of Rockets, Guided Missiles, airplane models or their components, under conditions approximating free flight into the supersonic range, enabling measurements of acceleration, velocity, lift, drag, and vibration.

Terminal Ballistic Tests evaluating impacts of missiles at high speeds into stationary targets. This includes warhead, warhead components (initiator, charge, metal parts, etc.) and fuze functioning, penetration, fragmentation, sensitivity, and telemetering tests against various thicknesses of target materials at different obliquities.

Tests of Ejectable Ordnance Components, such as warhead submissiles.

Physical Information

The track is actually a dual-rail monorail type, 2448 ft long. The cold-rolled steel rails are 2 × 1 in. in cross section with a 2-in. space between rails. See Fig. 3. Rail sections are 12 ft long and are attached in parallel by countersunk bolts to three point support saddles that permit horizontal and vertical adjustment. See Fig. 4. The foundation is a concrete wall of 24-ft sections tied together with steel reinforcing bars to allow for expansion and contraction due to temperature changes. The grade of the track approximately parallels the slope of the terrain which is 0.2 per cent upgrade.

Shoes carrying the test items are usually of aluminum and are machined to lock on the track. During firing no lubricant is used on the shoes or rails.

A full-length corrugated canopy covering the track allows for operation under various weather conditions.

Precision Aspects

Track alignment is obtained by sighting a theodolite over the track. This affords a minimum of lateral and vertical dispersion. The alignment is as accurate as instrument cross-

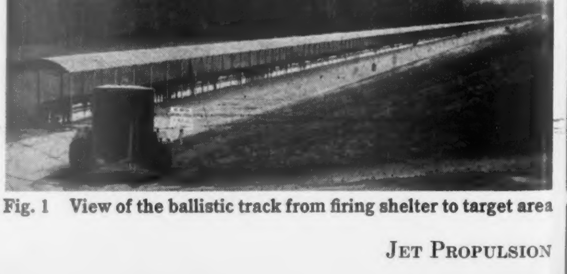

Fig. 1 View of the ballistic track from firing shelter to target area

Presented at the ARS Spring Meeting, Washington, D. C., April 4–6, 1957.

[1] Chief of The Aircraft Rocket Section.

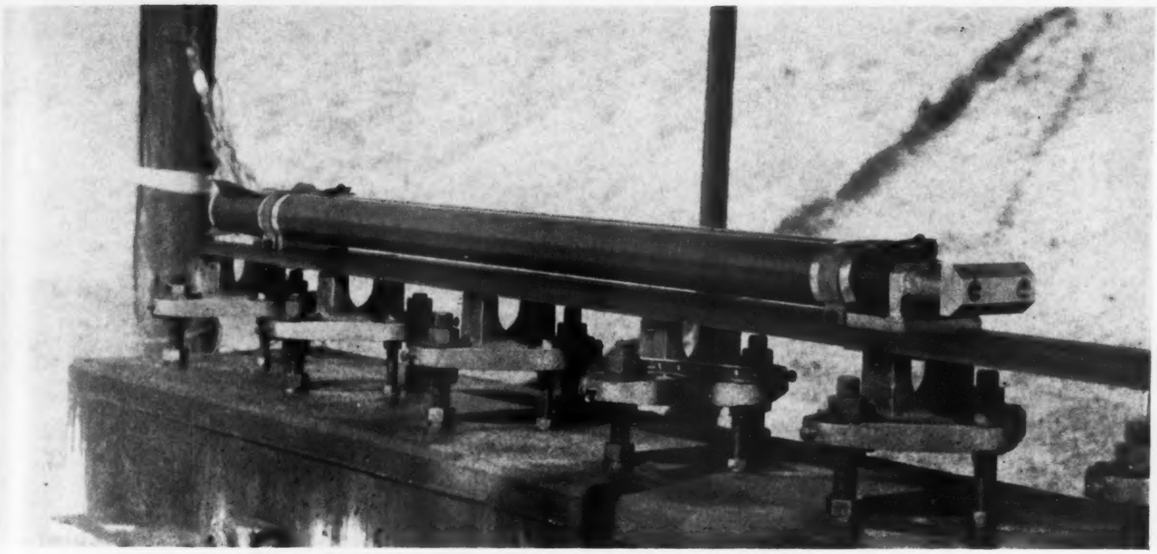

Fig. 2 A first-stage pusher combination of two rocket engines in parallel

hairs permit and approaches $\frac{1}{8}$ in. over the length of track. Leveling is accomplished in 14-ft sections to within 0.002 in. by means of a feeler gage.

Performance

Allowing continuous acceleration, possible runs are as indicated in the values shown in Table 1.

Boosters

Rocket boosters are used to accelerate test items along the track to required velocities. Various physical arrangements of boosters allow particular velocities to be obtained depending on test requirements. Boosters are fired at different footages along the track by contact knives cutting high potential screens. Temperature conditioning of boosters enables higher velocities by operation at elevated temperatures.

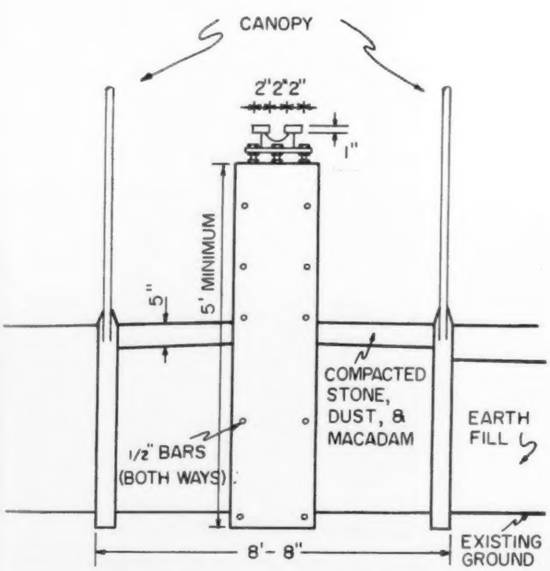

Fig. 3 Cross section of track structure

Table 1

Total weight of test system, lb	Weight of payload, lb	Acceleration, g	Velocity, fps
119	1.5	110	3625
235	45	50	1400
525	250	34	1100
2600	590	22	700

Separation Technique

In most cases test items are mounted above the front booster and are separated at the terminal end of the track by means of an explosive bolt arrangement (Fig. 5). The boosters may be deflected so they impact an earth mound and do not interfere with terminal ballistic evaluation of the round.

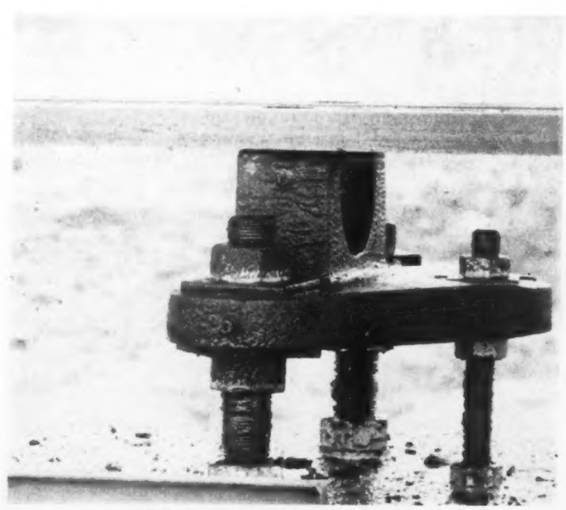

Fig. 4 Three point support saddles

Fig. 5 Typical booster arrangement showing explosive bolt at front booster

Instrumentation

Track events can be obtained downtrack at any preselected distance. Velocity performance can be measured by means of a magnetic-pickup coil system (Fig. 6). Telemetering, photographic coverage, and other types of instrumentation are available.

Sequence Control System

This system consists of a timer panel with adjustable time switches driven by a synchronous motor. Wire cables and terminal equipment are used for controlling cameras and for firing rockets.

Magnetic Pickup System

Velocities along the track are obtained by a magnet and coil system. As the magnet mounted on the front booster passes over coils along the track, electrical impulses are sent to the instrument trailer. The signal is recorded on a millisec time based on teledelto tape and a 16-mm film. From this, data velocities and accelerations can be obtained. Associated equipment such as oscillograph recorders and magnetic tape recorders are also available.

Photographic Instrumentation

On all firings a combination of Bowen, Mitchell, Fastex, Smear, Polaroid and standard motion picture cameras can be used to obtain data to determine functioning, angle of impact, events, etc. See Fig. 7.

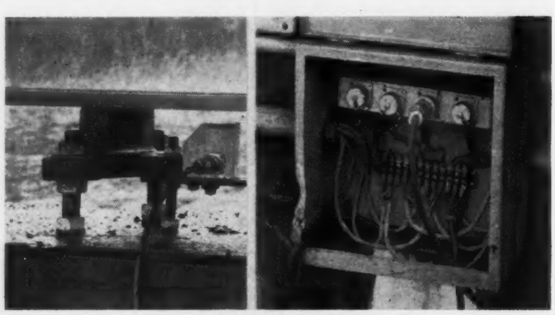

Fig. 6 Typical coil mounting on track

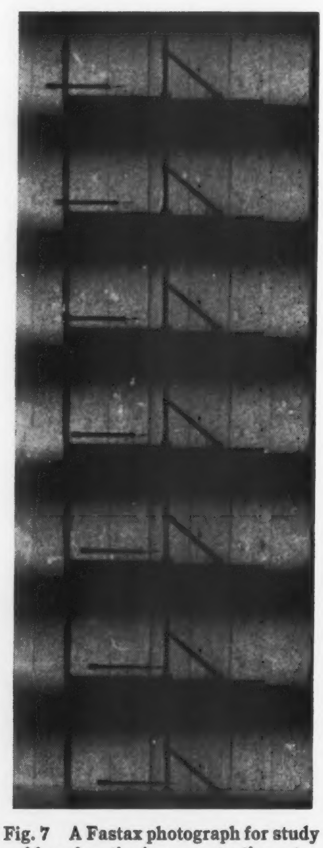

Fig. 7 A Fastax photograph for study of fuze functioning, penetration, etc.

Instrumentation Services

Development and proof services at Aberdeen Proving Ground have processing facilities and equipment available to support all photographic requirements.

Special and Associated Facilities

Controlled Temperature Conditioning

The temperature conditioning facilities are largely the stationary mechanical type ranging in size from a few cubic feet to over 1500 cu ft. Portable equipment is also in use. These facilities are capable of maintaining temperatures in the range of −90 F to 175 F over an extended period of time and within limits of ±2 F.

Assembly and Storage

A building designed for safety-approved assembly, loading, fuzing, boostering and static detonation equipment and personnel is available in the vicinity of the track. Diverse building and igloo magazines for storage of propellants and missiles are available.

Associated Facilities

The use of the ballistic track is enhanced by a number of supporting facilities, including the development and proof services of Aberdeen Proving Ground which consists of over 300 military and civilian engineers and scientists. The analytical laboratory division supplies complete project engineering services including evaluation and reduction of test data and reporting. Fabrication, machine shop and associated facilities are available.

Track Testing at the Air Force Flight Test Center

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Experimental Track Branch, AFFTC, Edwards AFB, Calif.

Introduction

THE development and use of tracks as a testing media have progressed from preliminary investigations to an operational tool in a matter of only a few years. Investigations in 1944, relative to launching carrier designs for the JB-2 and other missiles, were instrumental in establishing subsequent studies that resulted in construction of a 2000-ft track at the Air Force Flight Test Center (AFFTC) at Edwards, Calif.

The operational success and the high speeds obtained on this track precipitated further investigations that culminated in construction of the FATF (Free Air Test Facility) consisting of 10,000 ft of precision-aligned high speed track, built for the purpose of investigating aerodynamic parameters in the transonic speed range. The use of this track has transcended design expectations.

Deceleration Track

The 2000-ft track at the AFFTC was supplemented in 1947 with a hydromechanical braking system and since that time has been used principally for deceleration investigations. Tests have been conducted on aircraft seats, inertia reels, crash restraint harnesses, litter restraining devices and other equipment that is required to operate under high rectilinear deceleration forces. The first deceleration tests were conducted on dummies and animals, and later on human beings, to investigate crash effects on the human body. The most famous track test subject, Col. John P. Stapp, initiated aeromedical track work at this facility during this period.

Deceleration is obtained by presetting the hydraulic pressures in the braking system in accord with the required retarding force. The rocket sled carrying the test item is then fired into the braking area at a velocity between 220 and 300 fps. The sled automatically trips each programmed brake as it passes. Preset hydraulic pressure is applied to the brake shoes to develop the predetermined retarding force. The sled leaves the braking area at low velocity and coasts to a stop a few hundred feet away. In case the braking system fails to operate properly, a cable arresting device is located at the end of the track to effect recovery.

High Speed Track

The high speed track consists of 10,000 ft of precision-aligned, standard-gage, railroad-type track, with a water brake recovery system, space-time system, instrumentation and other supporting facilities.

The track itself is made of 115 lb per yard rail laid on continuous reinforced concrete beams. The beams are tied together with reinforced concrete ties every 9 ft. Theoretical consideration of the critical velocities of the rail and beam indicates that at the critical velocity of approximately 2000 fps, sleds weighing 13,500 lb can be operated safely. Considerably higher loads are possible at velocities other than critical. Parachute drag loads of 66,000 lb have been applied without difficulty and a project which develops a 100,000-lb drag load will be started presently.

A water trough, which is part of the water braking system, is located between the rails, extending 2000 ft from Station 80 to Station 100. The braking force is developed by the vehicle mounted water brake which scoops up water from the water trough and turns it through an angle of approximately 170 deg before it is discharged. Vehicles weighing as much as 10,000 lb have been stopped from a water brake entry velocity of 1000 fps. Higher entry velocities have been reached at lower weights. Larger and stronger water brakes are being constantly developed to keep abreast of ever increasing vehicle sizes and recovery velocities.

Propulsion for tests is provided by both solid and liquid propellant rockets. The majority of vehicles utilize solid rockets which are frequently fired in a programmed sequence to provide acceleration or speed patterns. Three liquid rocket engines are in current operation at the AFFTC. Two of these engines are the lox-alcohol type rated at 50,000 lb of thrust for 4.5 sec. One uses a red fuming nitric acid and aniline with

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Presented at the ARS Spring Meeting, Washington, D. C., April 4–6, 1957.

[1] Chief, Experimental Track Branch.

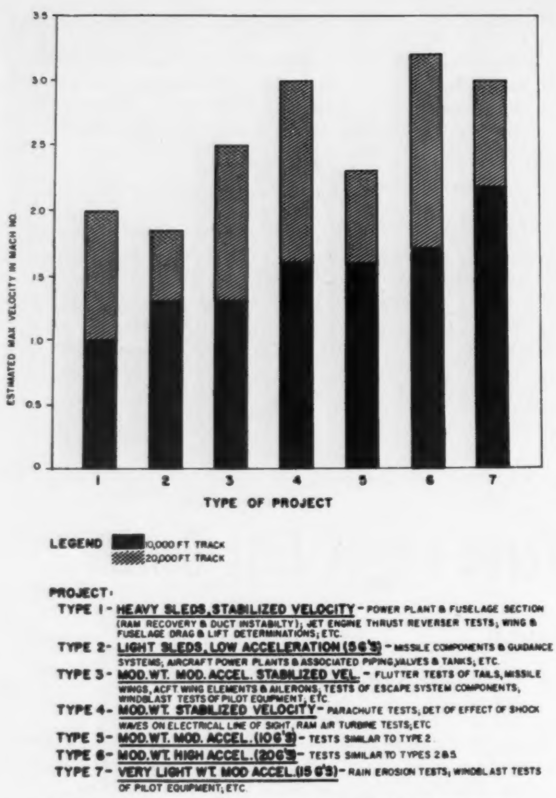

Fig. 1 Velocity vs. project type at AFFTC 10,000 track

a maximum thrust rating of 22,000 lb. Action has been taken to procure two additional liquid rocket engines with greatly increased thrust and with throttling control features.

Velocity, acceleration and rate of acceleration are determined accurately from the space-time system which consists of coils spaced along the track at 50-ft intervals. Each coil generates a pulse from the passage of a sled mounted magnet. The pulses are recorded with an accurate time base. Velocity can be determined within ± 0.2 per cent accuracy. A Doppler radar system is currently being checked out, which will not only improve accuracy, but will be capable of presenting data immediately following a run.

Instrumentation is primarily of the FM/FM telemetering type. Transmission of data can be accomplished on as high as 40 channels and parameter frequencies as high as 2000 cps can be recorded accurately. Strain gages, pressure transducers, accelerometers, load cells and many other primary transducers are available. Recording is done on tape recorders with playback to oscillographs or into automatic data assessing equipment. Direct recording of data on board the test vehicle has been done, but with difficulty. It is a problem to operate recording devices under the accelerating and decelerating loads reached on most track tests. Photographic data recording is an important part of track test work. Many types of cameras are used alongside the track, on test vehicles and along the metric camera range. The metric camera range consists of accurate camera mounts at 100-ft intervals along a line parallel to and 360 ft south of the track. This gives overlapping coverage for 2000 ft. Trajectories of hatches, seats and dummies are obtained from this camera range as well as the behavior of any sled-borne items such as parachutes, aerodynamic surfaces or flutter models. Eastman High Speed and Fastax cameras have been operating with color film to speeds of about 700 frames per second. A much improved data camera is under test to give higher resolution, better definition and a larger image at higher exposure rates.

Many other supporting items are required for a test facility, such as shops, handling equipment, blockhouses with rocket firing control systems, varieties of solid rockets, liquid rocket fuels and oxidizers, protective devices and development laboratories including instrumentation shops. One of the notable features at the AFFTC is the large variety of test sleds, or chassis, available for mounting test models. Some chassis are used for as many as four or five projects. For instance, one vehicle has been used for four seat ejection projects, another for three parachute programs and another for five full-scale tail flutter tests. When a test vehicle is available for a project it reduces substantially the cost of the project and the time required for test preparation.

Performance Envelope

The most spectacular feature of track operation is the high performance obtained. It is awe inspiring for an observer to witness from close proximity a test vehicle traveling across the terrain at a speed in excess of Mach 2 and to experience the resulting shock wave. Fig. 1 illustrates in general the performance and test variety capabilities of the AFFTC 10,000-ft track as well as the capabilities of the programmed 20,000-ft track.

New Facilities

A project has been approved to rebuild and extend the 10,000-ft track to a length of 20,000 ft and to provide additional supporting facilities. This development will extend the test speed capabilities to more than Mach 3 and will facilitate the testing of vehicles large enough to carry complete weapons systems.

The maximum speed for some projects on the present 10,000-ft track is limited by the combination of track length, recovery capability and allowable acceleration. The distance required to accelerate and decelerate varies with test objectives, but in cases where supersonic speed is required, the remaining distance in which the test takes place is limited. Extension of the track will increase this distance substantially. This increase in test time, or distance, does not require a corresponding increase in expensive accelerating rockets and therefore results in operational economy.

One of the most important features of the extended track will be the economy effected by the expanded use of liquid propellant rocket engines, which generally operate at a lower acceleration and at much less cost than a corresponding solid propellant engine. The longer track length allowable for acceleration facilitates the utilization of the liquid engine with its correspondingly smaller cost.

A comparison of track beam cross sections, Fig. 2, reveals

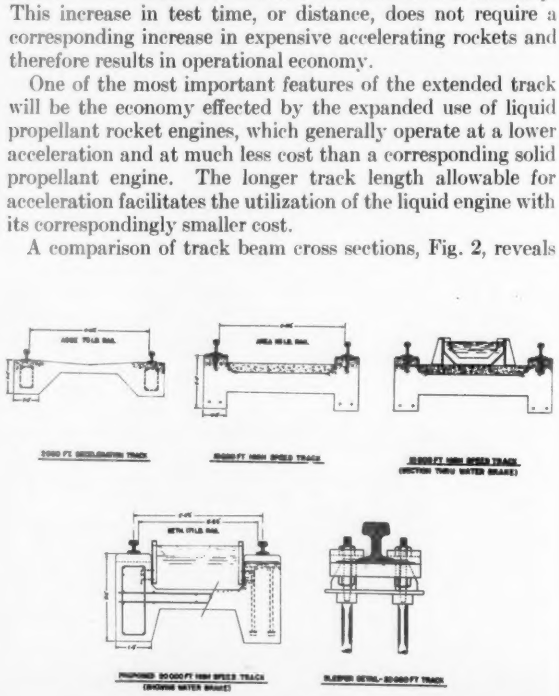

Fig. 2 Comparison of track beam cross sections

the continuous increase in performance and applied structural loads. The AFFTC 20,000-ft track will be able to handle 100,000-lb loads at the critical velocity of approximately 2900 fps. At higher and lower velocities, the allowable vehicle weight increases rapidly in accord with decreased magnification factors. Construction of the new track will be followed by careful instrumentation to corroborate the design calculations.

Planned facilities are extensive. Besides machine shops and office buildings, there will be interior space provided for simultaneous work on several test vehicles. Design and construction of the liquid propellant, oxidizer and high pressure gas storage and servicing system constitute a major project. Revision of the present instrumentation system is in process and integration of the system with the AFFTC base-wide data reduction installation (Project Datum) is expected soon.

Development Problems

There are many research and development problems connected with track operations which must be solved to permit the maximum possible economical use of this increasingly important test tool. Several major problems are those associated with the wear of slippers at velocities above 3500 fps, recovery of supersonic vehicles, aerodynamic interference effects caused by the operation of vehicles at supersonic speeds in close proximity to the ground and adequate and reliable propulsion systems. All such problems are being constantly investigated in an effort to improve track capabilities.

Propulsion

Although the backbone of track propulsion in the past has been the standard JATO units, it is becoming increasingly apparent that powerplants must be tailored to the track requirement. Several years of experience in the use of both solid and liquid systems at the AFFTC high speed track have evolved the requirement for a liquid propulsion "pusher" or "locomotive" to be used as a workhorse-type system for the majority of projects. This concept offers a very practical solution to the twin propulsion dilemmas of system versatility and adaptability to short-term projects. Economy is preserved, even though some weight penalties will result from separation of the propulsion system and test specimen. In this manner, a liquid system can be used interchangeably and with complete flexibility for a wide range of totally unrelated projects, relegating the use of expensive solid propellants to the marginal high performance projects. AFFTC plans for the development of liquid propulsion systems are directed along the lines of the pusher concept and include provisions for stabilization of velocities by means of vernier thrust control.

Many varieties of JATO units have been used at the AFFTC facility. The choice of units in the early period of track operation was normally based on their availability in military stocks. One particular unit, the only one available at that time, was condemned prior to its adoption at the high speed track. Operation with this unit resulted in an average of one explosion in about 20 firings. In recent years, the 2.2 KS 11,000 has been consistently used as a workhorse powerplant with good reliability. However, there is a need for larger, higher performance, more reliable units. Some features which must be available in a solid system are low weight, a standard short-time squib ignition system, small frontal area, high acceleration limits, constant operation over a wide ambient temperature range, and a long storage life without deterioration.

AFFTC experience has shown that liquid powerplants can be repeatedly fired with good reliability if reasonably good maintenance standards are maintained. Considerations of track requirements coupled with operational experience have resulted in operational specifications and design criteria for rocket powerplants that will be applicable not only to the expanded AFFTC facility but to other track installations as well. Many of these specifications arise from track-type operational requirements, but the most unique feature is the requirement that the rocket engine be throttleable and controllable in accord with a present program or by means of an operating transducer. This prominent aspect evolves from the track project plans that frequently call for either programmed or limited acceleration, velocity, dynamic pressure or other parameters for which sensing instrumentation can be provided.

Conclusion

Experience and imaginative thinking will lead to the increased use of test tracks for evaluation of aircraft or missile sections, their components, structures or powerplants. Effectively increasing the operational scope of track tests to attain optimum usefulness requires continual facility development. Therefore, each track is continually developing new capabilities, new skills and new powerplants, which lead to further demands for more speed, higher accelerations, better powerplants and instrumentation.

Track Testing at the Air Force Armament Center

RICHARD K. HENDRICKS[1]

U. S. Air Force Armament Center, Eglin Air Force Base, Fla.

RECENTLY, construction of a new track-type testing facility was completed at the Air Force Armament Center, Eglin AFB, Fla. This facility, the Damage Potential Range, is designed primarily for conducting terminal ballistic tests of air armament undergoing engineering evaluation and development at AFAC. Outstanding feature of this new range is the Damage Potential Launcher, a 2000-ft track which provides AFAC with its first supersonic track-type testing capability.

Initial track testing at AFAC began in 1954 on the rocket launching track, located on the rocket ballistic range. This track, 502 ft long and inclined at a 5-deg angle to a horizontal ground line, is used primarily to accelerate rockets to aircraft velocities in order that simulated aircraft launching of the rockets can be evaluated.

The Damage Potential Range is located about 30 miles northeast of the main base facilities at Eglin AFB. The broken terrain on which the range is located has an average elevation of 220 ft above sea level.

The range danger area is in the shape of a fan, with the track situated at the narrow end. The area extends down range approximately 6 miles from the muzzle end of the track and can be extended to 12 miles.

Presented at the ARS Spring Meeting, Washington, D. C., April 4–6, 1957.

[1] Chief, Weapons Test Equipment Section. Mem. ARS.

A railroad spur line, which passes within a half-mile of the range, can be used to haul in heavy test equipment and target material.

The prime capability of this new range is the Damage Potential Launcher, formed by a 2000-ft reinforced concrete beam which has an H-shaped cross section. The beam is inclined at a 0.6 per cent grade, the muzzle end of the beam being 12 ft higher than the breech end. Many of the design features of the G-4 and SNORT tracks located at the U. S. Naval Ordnance Test Station, China Lake, Calif., were utilized.

Of particular concern during the design of the track was the condition of the subgrade at the range site. The soil there consists primarily of fine and loosely compacted sand which is structurally very unstable. For this reason a 15-ft-wide trench extending the length of the launcher beam was excavated to a depth of at least 3 ft below the lowest point of the launcher. This trench was then filled and compacted to a suitable soil density with vibrating rollers.

A 2000-ft continuously welded rail, weighing 171 lb per yard, is set on each leg of the concrete beam at the standard railroad gage of $56\frac{1}{2}$ in. The rails are secured to the concrete beam by means of "sleepers" which are located every 30 in. along the length of the rails. The sleepers permit both horizontal and vertical adjustment of the rail for alignment purposes.

Rail lengths are jointed together by a pressure welding process. After welding, all rail joints were normalized and ground smooth. Each 2000-ft length of rail is rigidly anchored to the concrete beam at both ends of the track. The sleepers have been designed with sufficient strength to maintain the desired alignment tolerances despite the stresses caused by temperature changes of the rail.

First-order survey techniques were used in aligning the rails. Monuments, located on a base line parallel to the track, comprise a reference line. Using an optical alignment jig, the rail alignment was established within the following tolerances: 0.030 in. maximum horizontal deviation from a straight line over a 10-ft span; 0.030 in. maximum vertical deviation from a straight line over a 10-ft span; ±0.015 in. deviation from standard gage at sleeper locations.

In anticipation of future demands which may be placed on the launcher, the range has been designed with provisions for a 1000-ft extension to the breech end of the track.

The range control building, designed to protect its occupants from explosions or other hazardous conditions which may occur during a test, houses range communications, firing panels, instrumentation programmers, data recording equipment and timing equipment.

Five concrete barricades along the side of the track protect range personnel during squib-checking operations.

Three permanent instrumentation sites in the vicinity of the target area or muzzle end of the track are suitable for CZR-1 or Fastax cameras.

Two spotting towers located down range permit rough determination of location of test item impacts.

Rocket temperature conditioning chambers (with a range from 160 to −80 F), rocket static thrust stands, magazines and live ammunition assembly buildings are available at the adjacent rocket ballistic range, approximately one mile away.

Instrumentation and test equipment are available to handle basic requirements for the anticipated test programs. This equipment includes a magnetic pickup velocity measurement system, CZR-1 cameras, Fastax cameras, Warrick Streak cameras, a 2000-cycle flash lamp system, instrumentation programmer, data recording equipment and timing equipment.

This initial instrumentation will not be adequate to satisfy many future AFAC test requirements, and planning is under way to supplement the instrumentation array. Aerojet-General Corp. has completed a preliminary planning study for future range instrumentation and test equipment which, in part, proposes the use of micro-flash x-ray equipment, a Doppler radar, telemetry equipment, a ballistic pendulum, witness screens and fragment collectors. Also proposed, primarily for use as test vehicle instrumentation in conjunction with the telemetry equipment, are a variety of transducers for measuring temperatures, pressures, accelerations, vibrations and structural stresses.

Because of varied requirements for rocket-propelled test vehicles to be used at AFAC, a continuing test vehicle development program has been established. Chicago Midway Laboratories, affiliated with the University of Chicago, is participating in this program by providing prototype vehicle design and fabrication services. Three prototype vehicles were designed and fabricated for the initial tests conducted on the Damage Potential Launcher. The following information concerning these vehicles, though abbreviated to stay within security limitations, provides an indication of the type of vehicles required for AFAC track programs:

High Speed Monorail Test Vehicle (*Model #LM56-001*) was designed primarily for investigating track testing techniques which enable lightweight rocket warheads to be delivered to targets at high impact velocities. A 2-in. forward firing aircraft rocket warhead was selected as the test item. A two-stage, monorail configuration, with the rocket motors serving as structural members, was adopted for the vehicle. An aerodynamic fairing is provided at the front end to reduce air drag.

The vehicle has been designed so that upon reaching the desired velocity, the test item can be separated from the test vehicle by means of a small explosive charge. After separation, the test item proceeds to the target where terminal ballistic data are measured.

Crosswind Ballistics Test Vehicle (*Model #LD56-002*) was designed primarily for investigating capabilities of the damage potential launcher and instrumentation in support of crosswind ballistic testing of aircraft guns and rockets; and secondarily to determine the performance and reliability of retro-rockets and their ignition system.

The design utilizes a welded, tubular aluminum construction. The vehicle is designed so that a 20-mm gun barrel can be oriented in both horizontal or vertical crosswind angles. Seven 5-in. rocket motors propel it in a forward direction and five 5-in. retro-rocket motors provide a decelerating force on the vehicle. A single projectile is fired from the gun, when the vehicle reaches desired test velocities.

Track Shakedown Test Vehicle (*Model* (*#LM56-004*) was fabricated to provide a low cost test vehicle which could be used to check out firing circuits and instrumentation circuits. This single-stage monorail vehicle did not require any additional design time, since it consists of the forward section of the high speed monorail test vehicle.

Design Considerations of Two Large Liquid Rocket Sled Pusher Vehicles

H. DAVIES[1] and D. S. SMITH[2]

Reaction Motors, Inc., Denville, N. J.

Introduction

THE high speed rocket-propelled sled has gained in importance in the last few years as a research tool for testing at high Mach numbers and accelerations, while simulating flight with realism under recoverable conditions. With this advance, the development of suitable powerplants has also accelerated. Until recently, solid propellant rockets originally developed for other applications have dominated the field of rocket sled propulsion. However, while solids have an inherent simplicity, they are relatively expensive and have distinct limitations in power control.[3]

It has been found that for sled test programs requiring great versatility and large numbers of tests a liquid rocket propulsion system is highly desirable. For a large number of test runs, a liquid system can be operated with greater economy than a solid system.[4] In addition, future sled programs indicate a need for variable thrust to maintain constant velocities.[4] The liquid rocket powerplant has the advantage of being able to produce smooth accelerations without sharp steps and to maintain constant velocities, if required, by use of a sensing device to control thrust. This eliminates the dependency of the preset feature common to solid propellant powerplants.

At the present time, Reaction Motors, Inc., has a contract to design, develop and deliver two large liquid propellant pusher vehicles for the U. S. Air Force (Edwards AFB). These two vehicles are being developed to propel test sleds mounting large-size, full-scale aircraft components or structures over a wide range of velocities up to Mach 2. This paper describes some of the design considerations involved in the development of these pusher vehicles.

Requirements

Operational Requirements

The contract requirements call for two sleds, a transonic vehicle referred to as No. 1 pusher vehicle and a supersonic, or No. 2, pusher vehicle. The operational requirements are:

The No. 1 pusher vehicle (Fig. 1) must be capable of pushing a test sled weighing 5000 lb. The vehicle shall be able to attain and sustain, while pushing the test sled, any selected velocity between 900 fps and 1100 fps for 2 sec. The total rocket firing duration shall not exceed the equivalent of 6000 ft distance under dynamic operation. The vehicle and test sled shall also be capable of attaining and sustaining for 2 sec any selected velocity between 1350 and 1675 fps. The total rocket firing time shall not exceed the equivalent of 10,000 ft distance under dynamic operation.

The No. 2 vehicle (Fig. 2) shall be capable of reaching and sustaining a predetermined velocity ranging from 1100 to 2300 fps for 2 sec while pushing a 10,000-lb test sled and specimen. The total rocket firing time at any operational level shall not exceed the equivalent of 13,000 ft distance under dynamic operation.

The drag loads on both vehicles are predicated on typical drag coefficients obtained through past rocket sled testing at Edwards AFB.

Design Requirements

Design of the two sleds for transonic and supersonic speeds requires analysis of the stresses, aerodynamics, propulsion system, etc., similar to that involved in the design of any new high speed vehicle. However, the data available on design criteria of large sleds is meager and a considerable degree of extrapolation is required. As more information is accumulated through further testing, many of these problems will be resolved and an improved degree of structural efficiency may be possible.

The structural design of the No. 1 and No. 2 vehicles is based upon a combination of loads that occur under three different possible loading conditions. These are resolved into three basic cases which are (a) peak acceleration, (b) peak drag and (c) peak deceleration.

The structure is designed to withstand the worst combination of acceleration loadings in the three axes, longitudinal, vertical and lateral, at each of the three conditions. The highest positive design acceleration is 20 g and occurs in the longitudinal axis during the maximum acceleration phase for the No. 2 sled. The highest negative acceleration is -24 g and occurs on the same vehicle in the longitudinal axis during the "braking" or maximum deceleration phase.

In addition to the stresses imposed by the acceleration loadings on the propellant and gas tanks, which are part of the vehicle structure, appropriate safety factors are applied to the working pressures of these tanks to establish the design stresses resulting from pressure only.

The constant velocity requirement for sled operation dictates positive propellant tank expulsion. Constant velocity in its ideal sense does not alone require a positive means for expelling propellants from tanks. However, when coupled with both lateral and vertical accelerations as well as slight

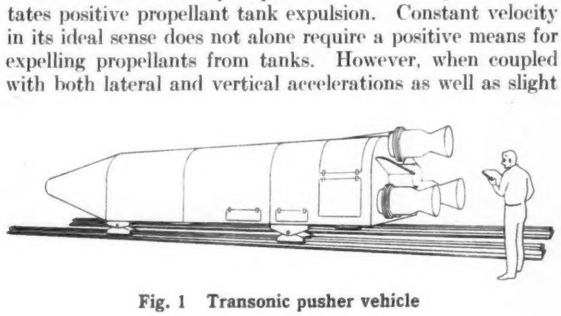

Fig. 1 Transonic pusher vehicle

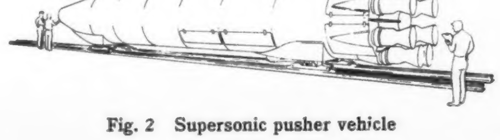

Fig. 2 Supersonic pusher vehicle

Presented at the ARS Spring Meeting, Washington, D. C., April 4–6, 1957.

[1] Principal Engineer. Mem. ARS.

[2] Project Engineer.

[3] Roth, C. E., and Poland, N. M., Third Supersonic Track Symposium—Liquid Rockets for Supersonic Sleds, Sept. 1956.

[4] Second Experimental Track Symposium—Seminar Reports and Abstracts of Papers, Sept. 26–28, 1955.

negative axial acceleration, it becomes mandatory to use positive expulsion during the constant velocity phase to prevent "unporting" or interruption of propellant flow.

The design temperature limit for the vehicles was not considered to be the significant problem. Since the pushers are to be used at Edwards, Calif., they will not be subject to low temperatures (very seldom below 32 F). The high ambient temperature limit is not expected to exceed 120 F. Moisture is not considered to be a major problem because of the very low humidity that prevails, 7 to 15 per cent, in this region, and the relatively little rainfall that occurs.

A major design condition centers around the constant velocity requirement, as it is necessary to provide some method of controlling thrust. When the required velocity is reached, it is necessary to decrease thrust to a level that will balance the drag and friction forces acting upon the vehicle. The programmed thrust requirements for the pusher vehicles involve two distinct types of thrust control. A large change, or step thrust, is required to decrease the thrust from the vehicle accelerating level to the level of sustained velocity, and a small vernier-type thrust control is required to maintain the final vehicle velocity within a $\pm \frac{1}{2}$ g tolerance for the 2 sec period. An additional program requirement is that gross thrust can be preset in increments of 10 per cent of the maximum rated thrust from the minimum to maximum thrust within a tolerance of ± 2.5 per cent.

Rocket engine cutoff is required to be a "deadman type control"—any failure of the control system that could cause a hazardous condition will stop propellant flow and safely shut down the engine. Normal engine cutoff is automatic after 2 sec of constant velocity operation. An external emergency cutoff device, such as a knife severing the main power supply cable, is operated by vehicle movement past a predetermined position along the track.

The basic malfunction philosophy being followed in powerplant design is:

The rocket engine shall, under any single condition of malfunction, start and operate in a stable, safe and reliable manner or shut down without presenting a hazardous condition that could cause damage to the vehicle. The basic single conditions of malfunction for which the engine must be nonhazardous are (a) power control malfunctions, (b) electrical system failure, (c) excessive voltage or frequency fluctuations, (d) electrical power interruption or fluctuation and (e) fortuitous subjection to conditions exceeding specified operating parameters (particularly applied to unporting).

The present contract for the two vehicles does not include the slippers and water brakes which will be developed independently. Existing slipper and water brake designs will meet the requirements of the No. 1 pusher. However, the larger vehicle, because of its extreme size and speed, requires new designs which will be undertaken by another contractor.

Under the present plan, there is to be a direct connection between the pusher vehicle and the test sled so that braking loads to both vehicles will be sustained by the pusher. This requirement may be modified in the future depending on the water brake development. If it is impractical to develop a water brake large enough to stop both vehicles in tandem, then two brakes will be used, one for each vehicle, and it may not be necessary to connect the two. This design requirement is being investigated further so that a firm decision can be made.

Design Aspects

Propellant Selection

Considerable attention was given to the selection of the best propellant combination for use in the pusher vehicles. The primary combinations considered were:

1 RFNA/NH_3 (anhydrous ammonia). This combination

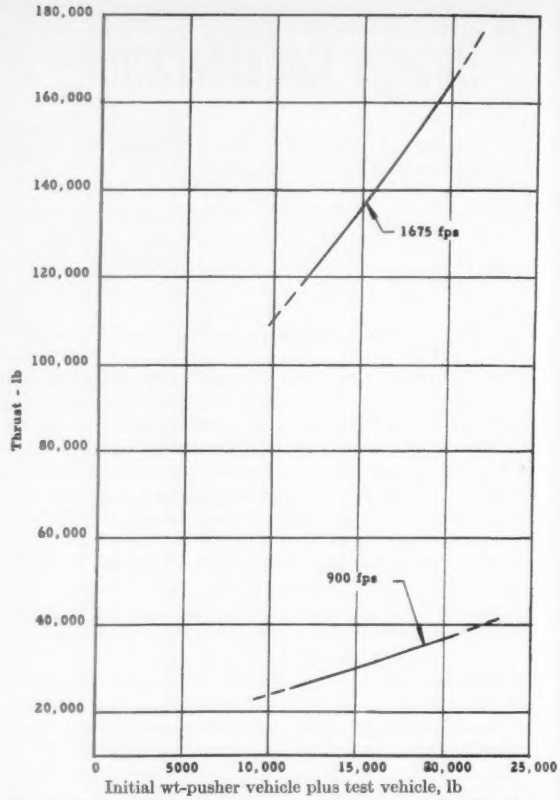

Fig. 3 Initial weight of transonic vehicle vs. acceleration thrust

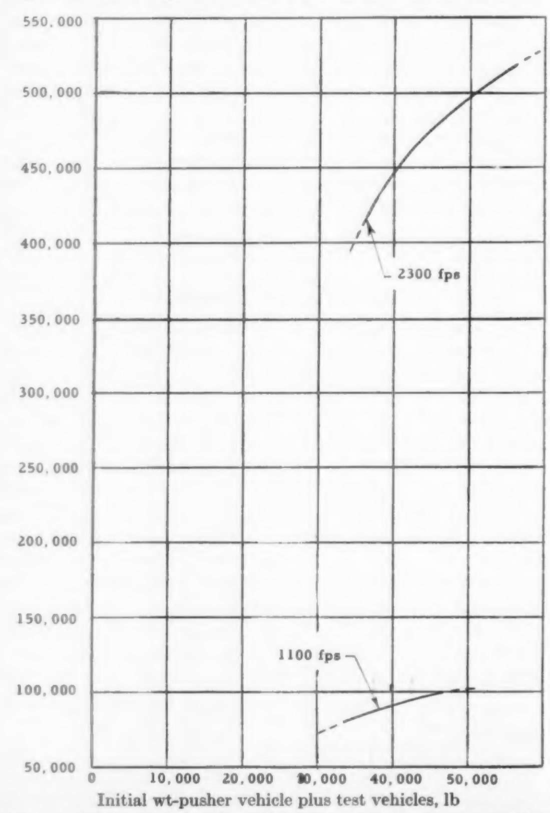

Fig. 4 Initial weight of supersonic vehicle vs. acceleration thrust

can be made hypergolic, i.e., spontaneously ignitable, by the proper use of a catalyst. It has the advantage of not requiring an electrical ignition system nor exceptionally close flow control during starting transients. However, it does require a relatively complex injector for high performance and combustion stability over a wide range of thrust and would be dependent upon operation reasonably close to the optimum mixture ratio. Therefore, in an engine requiring a high degree of throttleability, close flow control must be maintained over both oxidizer and fuel to maintain near design mixture ratio regardless of thrust level.

While RFNA can be handled safely with good operation procedures, it is far from an ideal oxidizer for everyday sled use.

2 RFNA/JP-4. This combination can be made hypergolic with suitable additives. The comments regarding RFNA/NH_3 are equally applicable except, in this case, the fuel is less toxic than anhydrous ammonia. However, due to the additives required and their relative high cost, the over-all propellant costs would be much higher than for propellant combination 1.

3 Liquid oxygen/JP-4. This combination is not hypergolic, hence it requires an external ignition source such as a liquid or solid propellant igniter for each thrust chamber. Each ignition system adds complexity to the over-all engine system, and the same comments pertaining to throttleability for 1, 2 still apply to this combination. This combination, however, has many advantages in handling and logistics.

4 90 per cent hydrogen peroxide/JP-4. This combination was selected as having the best over-all advantages. It is reliable and safe and has outstanding advantages for use in thrust variability. The detailed argument is as follows:

Because the oxidizer is a monopropellant, it is not necessary to maintain close control over the mixture ratio, and performance is relatively insensitive to wide variations of mixture ratio. The propellant combination can, in addition, be operated safely over a wide range of bipropellant mixture ratios (O/F) extending to infinity or monopropellant operation. The oxidizer can be decomposed simply by passing it through a catalyst bed and then injecting the fuel into the hot, decomposition products, i.e., steam and oxygen. By introducing all of the oxidizer into the chamber through a catalyst bed, almost 90 per cent of the total propellant flow is converted into a hot, high velocity, reactive gas which rapidly mixes and ignites with the incoming fuel, and thrust chamber safety is automatically satisfied by the use of fully decomposed H_2O_2.

The ability to operate on monopropellant alone is particularly important during engine shutdown because the fuel can be shut off first, and the peroxide decomposition gases effectively purge any residual fuel from the chamber, thereby eliminating the possibility of fuel leakage into the oxidizer side of the system.

This combination is not the cheapest, per se, but it is believed that it is the most economical considering every aspect of this application.

Vehicle Description

General

To meet the operating requirements for the pusher vehicles, it is necessary to establish the thrust levels required by the two vehicles and then determine the most suitable method of controlling the rocket powerplants to provide these thrust levels.

Figs. 3 and 4 illustrate the thrust required to accelerate the transonic and supersonic vehicles and test sleds at maximum weights to the maximum and minimum velocities within allowable distances. Drag vs. velocity curves for the two sleds, Figs. 5 and 6, were established using a C_dA (drag coefficient $\times$ frontal area) vs. Mach number, which was supplied by Edwards AFB. However, to determine the thrust, it is necessary to know the initial weight of the vehicle and

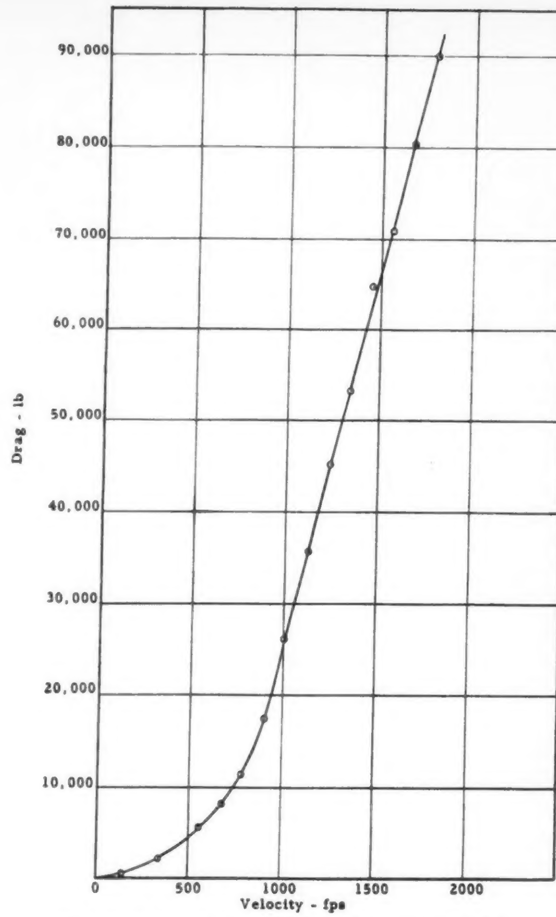

Fig. 5 Transonic test vehicle drag vs. velocity

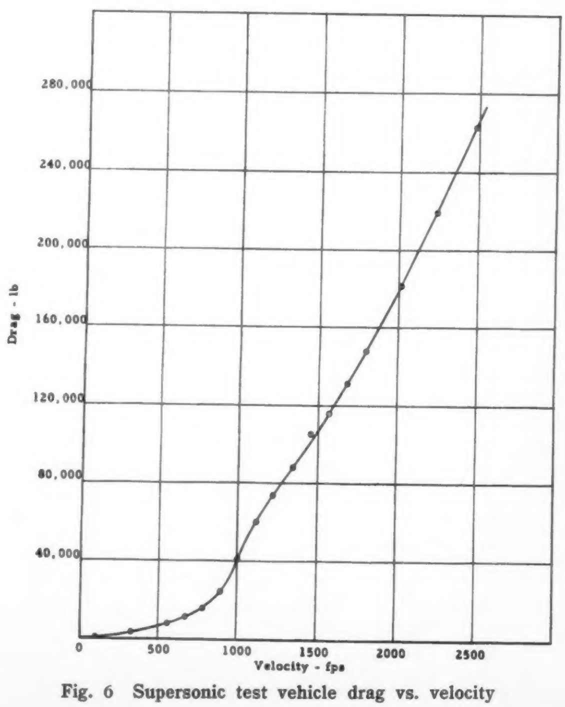

Fig. 6 Supersonic test vehicle drag vs. velocity

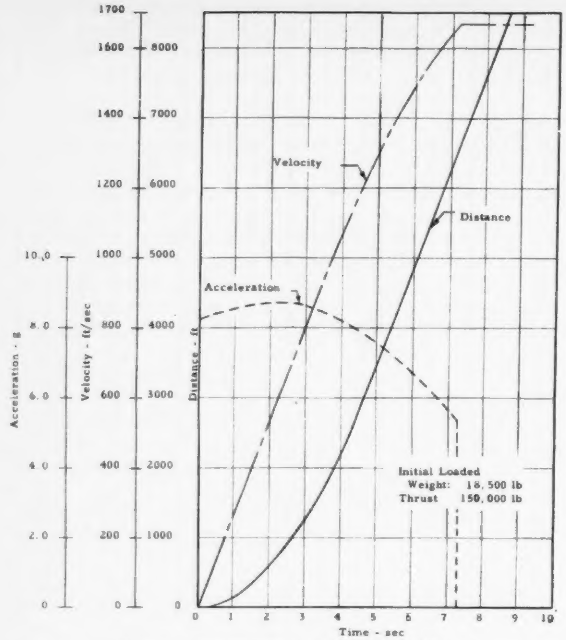

Fig. 7 Performance of transonic sled

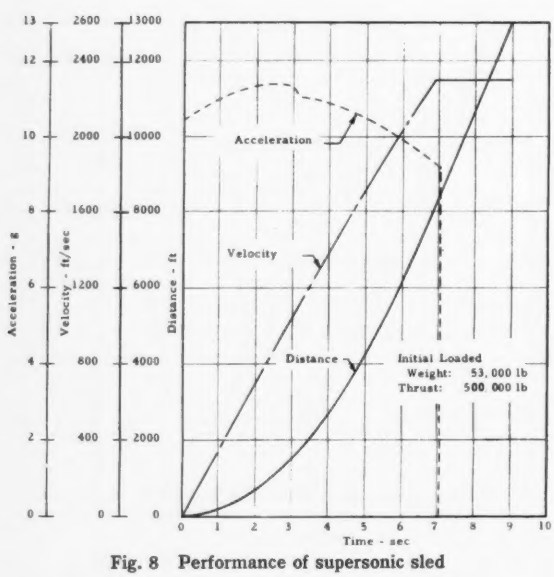

Fig. 8 Performance of supersonic sled

also at what rate its weight changes with time. Since the initial weight largely depends on the size of the powerplant, it is necessary in the formulation of Figs. 3 and 4 to use arbitrary pusher vehicle weights (maximum test sled weights are specified) to bracket an estimated over-all vehicle weight. The calculations assume the powerplants deliver constant thrust during the acceleration period, to maintain powerplant and control system simplicity.

Preliminary designs, taking into consideration specific impulse, minimum vehicle frontal areas and estimated weights, established the thrust levels for the No. 1 and No. 2 vehicles at 150,000 and 500,000 lb respectively. Fixing of these thrust requirements also established the maximum limits for the frontal areas and vehicle weights in the final designs. The performance of the two pusher vehicles at these thrust levels is shown in Figs. 7 and 8.

To provide the high thrust levels required for operating the pusher vehicles, a thrust chamber which has a range of 50,000 to 62,500 lb at chamber pressures of 350 and 450 psia, respectively, has been selected as the basic building block in developing powerplants of the required thrust output. Selection of this size is also predicated on the use, to some degree, of proved designs in order that the development time for the engine could be minimized.

Powerplant

The general arrangement of the powerplant for the transonic pusher vehicle in Fig. 1 consists of three thrust chambers clustered around the pressurized gas supply tank. Propellants are supplied by three oxidizer tanks and a single fuel tank. Each oxidizer tank supplies propellant to only one thrust chamber while the fuel tank is manifolded to all three. The single gas (nitrogen) supply tank is used to pressurize all four propellant tanks and to provide the necessary control pressure to actuate propellant valves, etc.

The general arrangement of the powerplant for the supersonic pusher vehicle in Fig. 2 consists of a cluster of eight thrust chambers arranged radially around the nitrogen tank. With the exception of the number of oxidizer tanks, the propellant feed system for this powerplant is essentially the same as the three thrust chamber powerplant in the transonic vehicle and uses the same components. In the eight thrust chamber system, four oxidizer tanks are used; each tank is manifolded to two thrust chambers. A single fuel tank feeding propellant to all eight thrust chambers and a single nitrogen pressurant supply tank constitute the balance of the tankage.

An outline of specifications for the two powerplants is shown in Table 1.

Table 1 Specifications for transonic and supersonic vehicle powerplants

	Transonic	Supersonic
Maximum thrust/chamber, lb	50,000	62,500
Maximum powerplant thrust, lb	150,000	500,000
Propellants		
Oxidizer	90% hydrogen peroxide	
Fuel	JP-4	
Chamber pressure, psia	350	450
Nominal duration, sec	8	9
Starting	catalytic and jet mixing	
Design altitude, ft	2300	2300
Chamber cooling	uncooled	uncooled
Estimated powerplant dry weight including tankage, lb	4,250	14,300

A schematic flow diagram of the eight thrust chamber powerplant is shown in Fig. 9. The flow diagram for the transonic vehicle is essentially the same except that only three thrust chambers and oxidizer tanks would be shown as described previously. The number of valves and control components have been kept to a minimum consistent with the programmed thrust requirements of the powerplant.

The propellant tanks are pressurized to the desired pressure levels by two nitrogen pressure regulators from the 3000-psi nitrogen tank. Hand valves are located in the pressurizing lines feeding each tank to permit removal of one or more tanks from the operating system; that is, when full powerplant thrust is not required for a particular test, two thrust chambers and their associated oxidizer tank can be eliminated from the operating system. At the outlet of each propellant tank, a normally closed tank shutoff valve is located. The use of

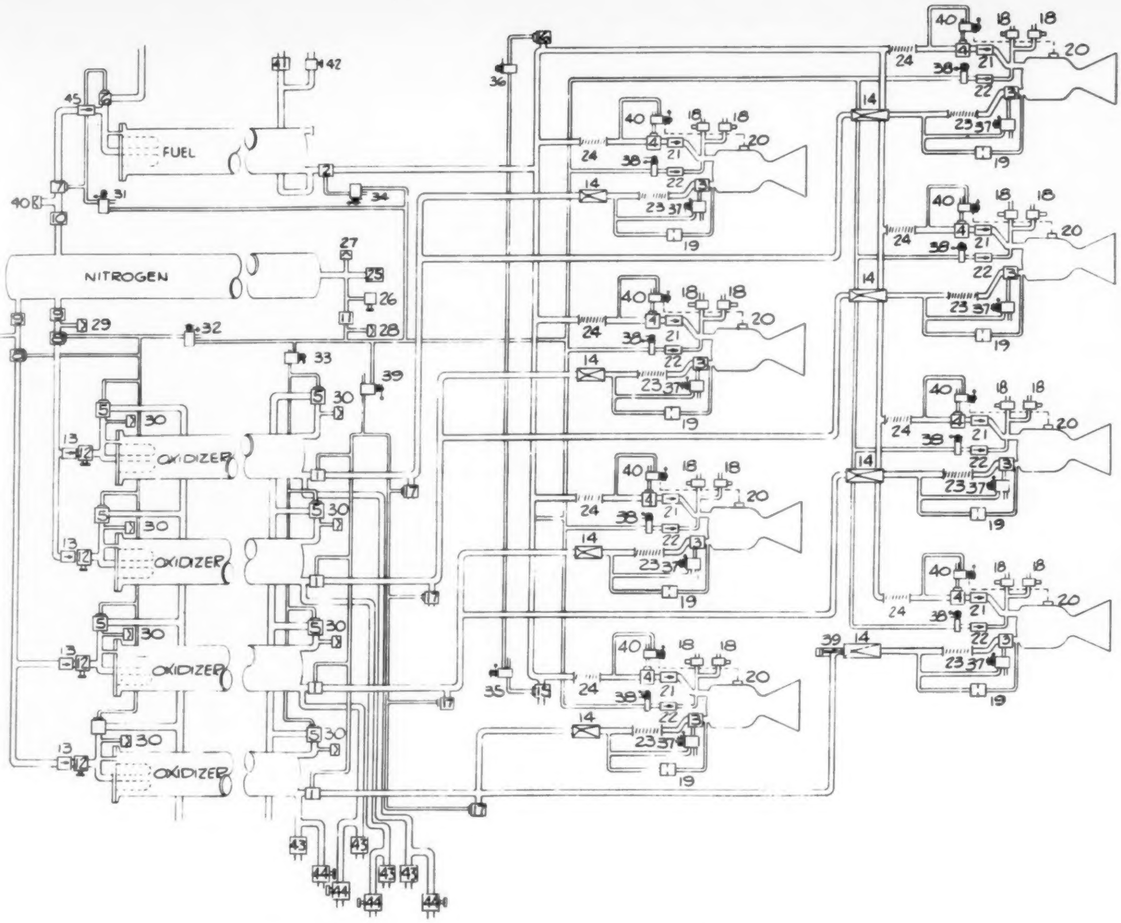

Fig. 9 Rocket powerplant system for supersonic pusher vehicle

1. Oxidizer tank safety valve (4)
2. Fuel tank safety valve
3. Oxidizer propellant valve (8)
4. Fuel propellant valve (8)
5. Oxidizer tank vent valve (8)
6. Fuel tank vent valve
7. Fuel tank pressurizing valve
8. Oxidizer tank pressurizing valve (2)
9. Oxidizer pressure regulator (2)
10. Fuel pressure regulator
11. Control pressure regulator
12. Oxidizer tank hand valve (4)
13. Oxidizer tank check valve (4)
14. Oxidizer cavitating venturi (8)
15. Fuel manifold drain valve
16. Fuel manifold bleed valve
17. Oxidizer manifold drain valve (4)
18. Fuel dump valve (16)
19. Catalyst preheat orifice (8)
20. Chamber pressure switch (8)
21. Fuel check valve (8)
22. Fuel manifold purge check valve (8)
23. Oxidizer flexible line (8)
24. Fuel flexible line (8)
25. Gas fill valve (pull-away disconnect)
26. Gas tank bleed valve
27. Gas tank safety burst disk
28. Control pressure safety burst disk
29. Oxidizer pressure regulator safety burst disk (2)
30. Oxidizer tank pressure safety burst disk (8)
31. Fuel tank pressurizing pilot valve
32. Oxidizer tank pressurizing pilot valve
33. Oxidizer tank vent pilot valve
34. Fuel tank safety valve pilot valve
35. Fuel manifold drain valve pilot valve
36. Fuel manifold bleed valve pilot valve
37. Oxidizer propellant valve pilot valve (8)
38. Fuel manifold purge valve (8)
39. Vernier chamber control valve
40. Fuel propellant valve pilot valve (8)
41. Fuel tank fill connection
42. Fuel tank drain valve
43. Oxidizer tank fill connection (4)
44. Oxidizer tank drain valve (4)
45. Fuel tank check valve

these valves, with a normally open drain valve between them and the individual thrust chamber propellant shutoff valves, insures against the possibility of accidental admission of propellants into the thrust chamber in the event of a single valve malfunction after shutdown or during servicing.

Cavitating venturi are located after the tank shutoff valves in each oxidizer line to provide flow control during monopropellant operation. During the constant velocity phase of operation, all thrust chambers, except one, operate on monopropellant only, and hence at lower chamber pressure. As a result, a cavitating venturi is used to maintain a constant oxidizer flow in this phase.

One thrust chamber acts as a vernier power unit. By means of variable oxidizer flow control valve the thrust is varied from maximum output at rated bipropellant operation down to near monopropellant operation or about 40 per cent rated thrust. The variable flow control valve is operated by a velocity control system which is described later. There is an oxidizer by-pass line around the thrust chamber propellant shutoff valve that permits a small amount of oxidizer to flow into the catalyst bed of the thrust chamber injector. This allows the catalyst bed to heat up prior to starting and makes it possible to efficiently decompose the oxidizer when the thrust chamber propellant valve opens. The fuel propellant valve for the thrust chamber is triggered by a pressure switch sensing chamber pressure. This assures proper decomposition of the oxidizer prior to fuel injection. Normally open fuel dump valves between the fuel injector and propellant valve permit rapid venting of fuel trapped between the valve and injector upon shutdown.

The thrust chamber assembly consists of an uncooled, ceramic-lined thrust chamber and an injection head. The in-

jection head consists of a catalyst bed, fuel injector and the necessary propellant manifolds.

The remainder of the system contains the necessary vent valves, fill and drain valves, safety burst disks, electric pilot valves, etc., necessary for the proper operation of the major components described. The choice of many components has been rationalized to reduce the number of different types.

Vehicle Structure

The detail design and fabrication of the body structure for both vehicles has been subcontracted to the Hunter-Bristol Corp., of Bristol, Pa., a company with considerable experience in sled structures.

The vehicles are cigar-shaped, deviating from this configuration only by reason of slipper undercarriage appendages, aft protuberance of the rocket thrust chambers and a small fairing protecting the forward ends of the chambers where they extend outside the envelope of the main body. The supersonic vehicle is essentially cylindrical with a conical nose whereas the transonic vehicle has somewhat flattened sides and top. The shapes are aerodynamically compatible since they present a clean surface unbroken except as unavoidably required for undercarriages and thrust chamber fairings.

Under a stiffened aluminum skin, an in-line arrangement of all major components of pusher and power equipment is maintained including in-line location of the prime structural member and carry-through to a push-pad for contact with the test sled. This internal arrangement is obtained by equally spacing the thrust chambers radially about a center member which serves both as a high pressure gas supply chamber and as the prime structure member of the sled. A similar radial positioning of fuel and oxidizer tanks about the center member forward of the thrust chambers and control compartment allows an in-line component arrangement. Oxidizer tanks, fuel tanks and all items in the control compartment are supported from the center structural member.

Basically, the design concept is to secure a vehicle with a minimum of eccentricity between the power source (thrust chambers) and the frontal push-pad, yet maintain an outside configuration which is aerodynamically efficient. The in-line arrangement of all components of the sled, excluding the undercarriage, and the location of the push-pad on the centerline of thrust, together with a uniform spacing of tankage, meet this concept.

The thrust chambers are cantilevered radially from a bulkhead which is fixed to the prime structural member. Side and vertical loads from the thrust chambers are taken directly to the prime member through this aft bulkhead. From the bulkhead, spaced between thrust chambers and extending aft, are gusset members which stabilize the bulkhead and transmit the thrust to the nitrogen tank.

The undercarriage consists of forward and aft structures and is cantilevered directly from the nitrogen tank. The aft installation is a box-type structure arranged to provide a rigid path for side and vertical load transmission from the slippers to the nitrogen tank. It also serves as a direct member for water scoop loads. A box-type carry-through from the base of the undercarriage to the prime member (nitrogen tank) provides torsional rigidity to the structure. The front undercarriage construction is similar to the aft assembly but is less complex due to the absence of a recovery device or water scoop at this point.

The pushing pad comprising the contact means between the pusher and the test sled is mounted on the front end of the nitrogen tank.

The oxidizer and fuel tanks are cradled in saddles mounted so that the aft saddle takes loads in all direction while the front saddle takes vertical shear only. This method of attachment negates adverse conditions that might arise due to unlike expansion or growth of the oxidizer and fuel tanks with respect to the steel pressurizing tank or main structural member.

Since the propellant tanks are long and cylindrical—20 in. diam and 25–30 ft long—they are adaptable to the use of pistons for positive expulsion. The oxidizer and fuel tanks are similar in design except for volume and length and are constructed of welded aluminum alloy, 6061-T6. One end of the tank has a removable concave head to permit insertion of the piston. No effort is being made to assure an absolute seal between the piston and tank wall since the gas pressure pushing the piston down the tank will be slightly higher than the liquid pressure. The piston is to be returned to its original starting position by pressurizing the downstream side with nitrogen pressure after each operation or test.

Estimated gross wet and dry weights of the transonic vehicle are 13,500 and 6600 lb respectively, and of the supersonic vehicle, 43,000 and 19,100 lb respectively.

Vehicle Control System

Since one of the basic purposes of the liquid propellant propulsion systems is to provide adequate variations in thrust, with a fine degree of control over the ultimate thrust level, the heart of the entire powerplant is the method of control and the control system itself.

It is evident that three separate control problems are involved:

1 The powerplant must be capable of adjustment between tests to provide the wide range of thrusts required to drive the pusher vehicles between the specified minimum and maximum sustained velocities.

2 The powerplant must be capable of large changes in thrust within a period of 1 sec or less during a run from the power level required for vehicle acceleration to the level required to maintain constant velocity.

3 The powerplant must be capable of relatively small variations in thrust during the constant velocity phase of operation in order to automatically maintain the sled velocity within a tolerance of $\pm\frac{1}{2}$ g for a period of 2 sec.

Based on the curves shown in Fig. 3–6, the constant accelerating thrust needed to bring the pusher vehicle and its test sled up to a particular velocity is roughly two times the thrust required to hold the desired constant velocity.

Taking the supersonic sled as an example, to accelerate the pusher and test sled to a velocity of 1600 fps within the specified length of track, a constant thrust of about 240,000 lb is required. Several methods for supplying this thrust and then reducing it to 120,000 lb for the constant velocity can be used, but the following method is believed to be the best.

The method of reducing thrust is basically a switch from straight bipropellant operation to monopropellant operation with the vernier thrust chamber continuing to operate bipropellant except at a reduced thrust level. Four thrust chambers operating at full rated thrust will provide 250,000-lb thrust, or somewhat more than the estimated requirements. Upon reaching the required velocity, 1600 fps, three thrust chambers would have their fuel supply shut off and they would revert to monopropellant operation producing about 65,000 lb thrust. To make up the remaining thrust requirement of 120,000 lb thrust, the vernier thrust chamber would be required to produce 55,000 lb thrust or 88 per cent of rated thrust.

This method can be applied to all velocity requirements by different selections of the number of thrust chambers used. Bipropellant plus monopropellant operation is advantageous since it requires shutting down only about one-eighth rather than one-half of the total propellant flow. This allows the change in thrust level to be made rapidly without serious hydraulic hammer occurring in the propellant system, resulting in a simpler, more reliable valving and manifold system.

In addition to the gross thrust changes that take place at the end of the vehicle accelerating period, some form of thrust

control is necessary during the constant velocity phase to maintain this final velocity within the $\pm\frac{1}{2}$ g tolerance of the desired value. The drag curve is a self-regulating curve, i.e., a relatively large change in thrust is required to promote a small change in velocity. Nevertheless, some form of variable thrust is needed for final adjustment when the velocity is reached. Also, factors not apparent from the drag curve may require some variation in thrust during the final 2-sec period to maintain the velocity within the specified tolerance. This is particularly evident because it is most difficult to predict with a satisfactory degree of accuracy the drag developed by the various test specimens.

Three methods of continuously varying thrust can be considered: Mounting the thrust chambers in a gimbal, use of a deflector in the rocket exhaust and throttling of one thrust chamber.

Gimbal Method. Gimballing a thrust chamber can provide thrust control by utilizing a component of the full thrust. However, this method of thrust control is not considered particularly desirable due to both the increased mechanical complexity of the system and the problem of obtaining rapid response. The additional components required for a control system of this type would decrease the over-all system reliability and increase its weight. A major objection to this system is the excessive track loads that could develop because of the thrust vector forces not parallel to the axis of the vehicle.

Exhaust Deflector Method. This type of control, like the gimballed thrust chamber, has the advantage of maintaining thrust constant while the resultant direction and magnitude of the thrust vector are varied. A disadvantage of this system stems primarily from the difficulty inherent in mounting a deflector plate in the jet stream capable of withstanding the necessary loads. The additional structure required for such an installation would not only complicate the vehicle chassis design but would also add considerable weight.

Throttling Method. As a result of the extreme flexibility of the hydrogen peroxide–JP-4 propellants evidenced by the ability of this combination to operate over a wide range of mixture ratios, an attractive and natural method of providing variable thrust control is by means of throttling one of the propellant flows. The system chosen is of this type and throttles the oxidizer flow directly without affecting the fuel flow. As the permitted range of O/F values is wide, this system results in a very simple control. The system consists of a throttling venturi operated by an electro-hydraulic actuator. The amplifying system will consist of an electronic or magnetic amplifier driving an electro-hydraulic valve metering hydraulic fluid to a ram which positions the actuator. Since the fuel is already under pressure, it can be used as the hydraulic fluid. For this particular control system, a power supply will have to be carried within the pusher body to operate these components. For the 8 or 9 sec duty cycle, storage batteries with a high discharge rate ability can be used for electrical power.

Velocity measurement, because of the accuracy requirements, will be the most difficult aspect of the control system. Several methods of measurement have been considered but were discarded as unsuitable. These methods included:

Dynamic Pressure Head as a Velocity Function. An apparently obvious method of measuring velocity would be to use a pitot tube pickup such as those used in aircraft airspeed measuring systems. However, closer examination of the accuracy requirements of the present system and especially the necessity for having the test vehicle apparatus operate in an undisturbed velocity region appears to preclude the use of the pitot tube. For example, if the nose section of an aircraft were to be tested at supersonic speed this section would set up its own shock wave pattern which would seriously affect the accuracy of any pitot tube pickups behind this shock pattern. Conversely, if the pitot tube were put ahead of the test vehicle the pitot tube shock pattern could conceivably interfere seriously with attainment of accurate data on the test specimen. A further examination of the thermodynamic and compressible flow equations relating conditions before and after shock waves and for subsonic and supersonic flow indicate that so many factors enter into the calculation as to make virtually impossible a reliable speed indication.

Radar. A second method which is considered for velocity measurements would be based upon the use of radar and/or the Doppler system. Either vehicle-carried or ground-located radar equipment would measure distance as a function of time and would feed the appropriate signals into the vehicle velocity control system. In general, this method is complex and involves high maintenance requirements.

Oscillating Light Source. A third suggestion involved the use of an oscillating stationary light source which by virtue of the oscillation would vary the intensity as seen by the sled and therefore permit an indication of velocity as a function of the rate of change of intensity of the light. Again this system has a tendency to suffer from factors which would interrupt the light source, such as sand and dust, and the possible necessity for the use of photocells and other devices which tend to make the system rather complex.

Rolling Wheel. The fourth method suggested the possibility of a spring-loaded wheel rolling along the top of the rail and by mechanical gearing of belting driving a tachometer generator which would produce a voltage proportional to speed. The overwhelming disadvantage of this system would be that surface speeds of 2300 fps would be required on the wheel. This same disadvantage would apply to the case in which a cable attached to the ground was unwound on a drum mounted on a sled, because somewhere in the system the equivalent surface velocity of 2300 fps would have to be attained and involves the same mechanical limitations.

Two other systems based upon reference feedback and comparison can be considered. Type I essentially involves an accelerometer to measure the rate of change of velocity, an integrator which will integrate acceleration to give velocity, and a switching device to introduce the acceleration feedback at a fixed ratio of the reference velocity setting. This system has the advantage of permitting a completely self-contained sled unit to be used not requiring any fixed equipment along the track. The accelerometer is actually a standard component which can be commercially procured and the integrator will be an operational amplifier type such as is commonly used in analog computers. Such devices are basic building blocks of computers and have integrating accuracies on the order of $\frac{1}{10}$ per cent over a period of several minutes. Accelerometers specifically designed for missile use, and integrators for airborne computers, are available so that procurement of these components should be straightforward.

The Type II system is based primarily on the use of digital counting equipment. It depends on a series of ground-mounted magnetic units which produce pulses as the sled passes over. The pulses are used to govern the time of a counting circuit, where the counting circuit is fed by an oscillator which produces a train of pulses at a megacycle rate. The ground pulses limit the number of these high frequency pulses which feed into a pulse accumulator. The pulse accumulator will incorporate in it a capacitive type of unit which produces a voltage proportional to the total number of pulses which are fed in during a given counting period. In the reference part of the system, reference velocity is used to determine the width of a gate circuit which again determines the total number of pulses which will be accumulated in this given gate width. This again feeds into a pulse accumulator to produce a reference voltage against which the system governs. Both the gate circuit and the flip-flop circuit are fed by the same pulse train so that variations in pulse train frequency have a negligible effect on the accuracy of the system. An important feature of this approach is that the system can have very high accuracy because pulses can be determined with ± 1 count, even for very high pulse rates. Out of the pulse

accumulators, analog-type voltages are produced; these are compared and act through the limiter circuits and through a differentiating circuit in much the same manner as the Type I system and satisfy the basic feedback control system requirements.

The Type I system involving an integrating accelerometer has been chosen as the best over-all approach. It is an entirely self-contained unit and requires no track modification installations or special maintenance.

General

The vehicles are designed for a minimum degree of overhaul and maintenance. Provisions are to be made for ready access to all functional components with particular attention given to convenient access to the engines bay and the area of pressure regulators, tank vent valves and engine control components. Servicing and propellant loading panels are provided on the sides of the vehicles at accessible locations. Oxidizer and fuel servicing facilities are separated so that one is on one side of the pusher and the other on the opposite side. The service panel is to include both fill and drain connections for the tankage.

All lines, cavities and tanks are capable of being completely drained. The bay between the propellant tanks and thrust chambers is to be provided with generous venting facilities and care has been taken so that leakage from a flange or joint containing one propellant cannot fall directly upon a line containing the other. Particular attention has been paid to the draining of the fairing panels enclosing the vehicle body, so that an accumulation of fluids cannot occur should leakage be experienced. Lifting eyes are provided for convenient lifting and towing of the complete pusher vehicle and all panels and access locations are designed for maximum accessibility.

Due to the chemical activity of hydrogen peroxide with foreign matter, particular emphasis will be given to keeping the internal powerplant system free of dirt. This is particularly important because of the desert-type country in which these vehicles will operate. These conditions very often create a dusty or sand-filled atmosphere that would easily enter a fluid system if filters or check valves are not employed to maintain a sealed system.

Conclusion

The large transonic and supersonic pusher vehicles being designed and developed by Reaction Motors, Inc., meet a requirement of high speed track testing that would be almost impossible to meet by other means. The propulsion system versatility is outstanding in that relatively high loads can be propelled over a wide range of velocities and at high speeds. The propulsion system is also adaptable to acceleration control or limitation in addition to being able to maintain specified constant velocities. Not only are these pusher vehicles versatile in speed control but they can be utilized interchangeably with a large number of track testing projects. The liquid rocket propellant propulsion systems have a significant advantage over equivalent solids in the cost of propellants consumed. To date, solid propellants have not been able to achieve the relatively low cost per pound of the more commonly used liquid propellants. For a large number of tests this factor becomes increasingly important, particularly as the thrust levels required for testing rise.

At the present state of propulsion technology the liquid rocket powerplant is the only solution to the requirement of variable thrust to maintain given velocities in vehicles of large size.

Liquid Rockets for Supersonic Sleds

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Introduction

THE rapid increase in testing requirements and the advance in techniques over the past few years have accelerated the development of sled powerplants. Early sled test programs involving light payloads and a relatively small number of runs were able to utilize solid propellants. In many cases the sleds could be designed to accommodate armament rockets which were available in large quantities. The runs could be tailored approximately to fit test needs by the proper combining of solid propellant charges in programmed stages.

The success of the rocket sled as a test tool has resulted in sled programs now being planned that involve hundreds of runs of relatively long duration. It is in this field that the liquid rocket is superior. The relatively high first cost may be more than offset by the low cost of liquid propellant per run, and the run is more uniform and predictable than with staged solid propellants.

Two liquid sleds designed and completed by Aerojet are now in operation, Models AJ10-28 and AJ10-36. They are intended for use on the SNORT track at China Lake, Calif. Aerojet is now building the rocket engine and tankage for a third sled, Model AJ10-33, for the Coleman Engineering Co., to be used on the SMART track at Hurricane, Utah.

Presented at the ARS Spring Meeting, Washington, D. C. April 4–6, 1957.

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Summary

The design of a liquid system for powering a supersonic sled involves considerations of stresses, aerodynamics, propulsion-system parameters, material evaluation and other basic functions associated with the design of any new system. Although supersonic sleds have previously been powered by liquid rockets, the practice is relatively new. The understanding of an environment which is neither that of a free-flying missile nor that of a statically operated rocket is a challenge to the designer of a supersonic sled. Once the selection of the particular liquid rocket type has been made, the determination of the design is a function of the requirements to be satisfied. The preliminary design phase involves the determination of the impulse-to-weight ratio of the rocket and sled system, together with drag, track length and track friction.

Design Requirements

The design requirements for the AJ10-28 and the AJ10-36 sleds, while not identical, covered the following ranges: Payload, 100–1000 lb; acceleration 4 to 6 g; maximum velocity, 1400–1600 fps; deceleration, 12 to 20 g; operating temperature range, 32–130 F.

The AJ10-33 sled represents a considerable advance: Payload, 1500–2500 lb; acceleration, 9–10 g; maximum velocity, 2400 fps; deceleration, 80–100 g; operating temperature range, 32–130 F.

Selection of Rocket System

To minimize the development time required, well-established systems and components were adapted. The selection for all three sleds was a cold-gas-pressurized bipropellant system utilizing a proven 35,000-lb-thrust chamber, ceramic-lined. At the time the sled designs were initiated, over 600 tests of similar systems had been made on other applications. The AJ10-28 and the AJ10-36 sleds are each equipped with one thrust chamber, while the AJ10-33 uses three chambers (Fig. 1).

Additional requirements included the need for variable duration, variable thrust, repeated operation, command shutdown and fail-safe control. In conjunction with these requirements, the factors of complexity, servicing, and maintenance were evaluated in an effort to produce sleds capable of repeated operation and with a minimum of servicing effort.

Propellants

Selection of the propellant combination was based on the tests mentioned previously. The propellants are inhibited red fuming nitric acid as the oxidizer and JP-X as the fuel. Approximately 20 lb of mixed aniline and furfuryl alcohol is used as the starting fuel. The JP-X consists of 40 per cent unsymmetrical dimethylhydrazine and 60 per cent JP-4. The operation of the particular thrust chamber selected for this combination has been entirely satisfactory and produces a nominal specific impulse of 210 lb-sec/lb. The operating mixture ratio of 3.6 to 1 was selected as yielding the best combination of impulse and density loading within the range of operation evaluated. The characteristics of the propellant combination are such that no purge is required either before starting or after shutdown. The resulting simplicity of the rocket system permits a saving in weight and a decrease in servicing time and maintenance requirements.

Operation of the thrust chamber in other systems had proved its capabilities by repeated tests of from 5 to 40 sec duration. Tests of the sleds have verified the satisfactory operation of the system in general and of the thrust chamber in particular. Operation of the sled rocket system has been evaluated for durations from 2 to 10 sec, and the starting, steady-state operation, shutdown and malfunction conditions encountered have all been satisfactory. The environmental suitability of the system was demonstrated to be adequate to meet the design requirements of operation from +32 to +130 F.

The design of the booster system was based upon a fail-safe requirement and permits safe shutdowns in the event of electrical power loss. In addition, command shutdowns may be made at any predetermined track position by the use of a knife switch, which breaks the electrical firing circuit. The thrust level has been evaluated over a range of ±15 per cent of the rated 35,000 lb.

Structure

Design of the sled structure was directly involved with the rocket system design because the propellant tanks and the pressurizing-gas tanks form an integral part of the main load structure of the sleds. The three sleds differ structurally: The AJ10-28 sled with its model-carrying forebody constitutes a single rigid frame with four points of track support, while the AJ10-36 and AJ10-33 are articulated, with the payload sections mounted on their own track slippers and attached to the rocket sled by pin joints. The aerodynamic characteristics of the forebodies and the sleds were based upon the requirement for zero lift. Provision was made on the AJ10-28 forebody for aerodynamic trim in the event that lift was encountered. An artist's conception of the AJ10-36 sled is shown in Fig. 2.

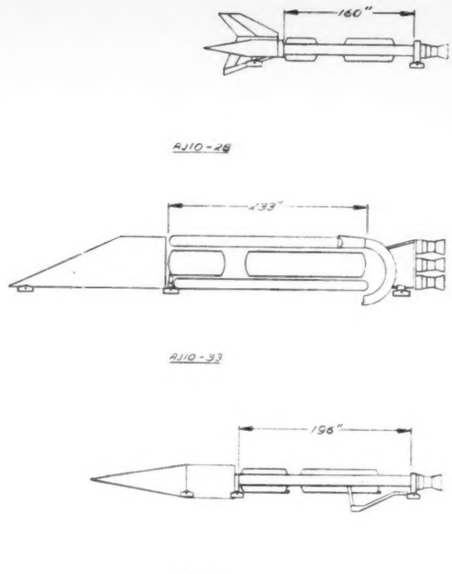

Fig. 1 Liquid rocket sleds

Both the AJ10-28 and the AJ10-36 utilize water brakes with rectangular inlets and horizontal 90 deg returns. The AJ10-33 uses a variable inlet with a vertical 180 deg return. To minimize weight and to meet the requirements of velocity, acceleration and payload, the material selected for the propellant tankage was aluminum alloy. To provide adequate strength to take the main thrust and to meet pressure ratings, the pressurizing tanks were made from 4130 steel. The approximate pressure ratings are 2500 psig for the gas tanks and 600 psig for the propellant tanks. Internal baffling was installed to inhibit sloshing and to prevent uncovering of the outlet during the various operational phases. The nose, or forebody, sections are of semimonocoque construction with riveted aluminum-alloy skin. Requirements for the installation of the payload and of telemetric and photographic equipment were different for the three sleds.

Testing

Static and dynamic testing were planned to prove the design of the sleds. The static-test phase was used to demonstrate the operating characteristics of the rocket system. Starts, steady-state operation, shutdowns, malfunction conditions, and environmental suitability were all evaluated. The test results indicated satisfactory operation under all conditions and conformance to the design requirements. The dynamic-test phase is being used to demonstrate the satisfactory operation of the rocket under the same conditions, plus the actual track run. Sixteen dynamic tests have

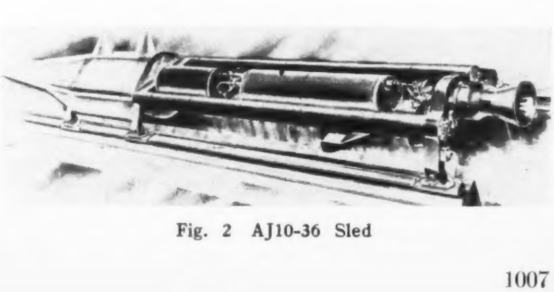

Fig. 2 AJ10-36 Sled

been completed using the AJ10-28 and the AJ10-36 sleds on the SNORT track. The operation of all systems was, in general, satisfactory, and the actual performance points fall close to the predicted curves.

The acquisition of data during the static tests was made by conventional direct-wire connections between the sled and the end instruments. The analysis of the data verified design conditions and indicated the expected high degree of accuracy and validity. The sled operating information during the dynamic testing was transmitted and received with a telemetric system. The evaluation of the rocket data was straightforward, and the correlation of the results was excellent. Other instrumentation, installed to determine the general environmental characteristics, yielded data which were more difficult to evaluate. These data, from velocity and acceleration transducers, clearly pointed out the need for cautious use of the information, utilizing engineering judgment and experience.

Design and Fabrication

The basic designs of the sleds were arrived at by considering the track length, acceleration, braking deceleration, and maximum velocity (Figs. 3 and 4). These plots indicated the duration of thrust required, the total propellant weight and the allowable sled gross weight. Since the greater part of the sled dry weight is due to the propellant and pressurizing-gas tankage, it was apparent that every effort should be made to produce tankage of minimum weight. To meet the design pressure requirements dictated by the thrust level and duration, and also to meet the expected vibration and acceleration loads, the materials selected were 6061 heat-treated aluminum alloy for the propellant tanks and 4130 steel for the gas tanks. The 6061 aluminum, heat-treated to the T-6 condition, offered the best design criteria and highest probability of successful manufacture for propellant tanks when the designs were conceived. In addition, aluminum is a readily available, noncritical material that is compatible with both the oxidizer and the fuel.

Since the load requirements varied for the sleds, the original tank designs for the AJ10-28 and the AJ10-36 sleds consisted of 24-in. cylindrical sections with semielliptical heads, internal stiffening rings for transverse and vertical loads, and baffles. The AJ10-33 tanks were similar, but of slightly greater diameter, with external rather than internal stiffening rings, and with additional internal baffling to meet the multioutlet requirement for three thrust chambers. The wall thickness, $\frac{3}{8}$ in., was dictated by stress, weight and material-availability requirements. The critical design stress of 37,800 psi, ultimate, assuming a 0.9 weld factor, was indicated to be the hoop stress. Design burst pressures were in the range from 1140 to 1250 psi. Since the welding evaluation indicated excellent results with machine welds and slightly less reliability with hand welding, some difficulty was anticipated with the many bosses and outlets required but not with the longitudinal closure welds. The functions of various bosses were combined where possible; for example, utilizing the same outlet for ullage control, servicing return, and vents.

Drawing-up of satisfactory controls and standards for the manufacture of these tanks, particularly with regard to x-ray inspection, has been difficult. The application of known laboratory-scale techniques in full-scale fabrication was found to be very difficult and the techniques for evaluating inclusions, porosities and nonfusions have been developed largely from experience. Even heat-treating, weld back-up requirements, grinding out for repairs, and allowable numbers of repairs also presented significant problems. The investigation of fatigue under field conditions is now under way. Except for the stringent welding technique requirements, selecting a fusion material is the most critical problem. The present 4043 weld rod has undesirable qualities when used in conjunction with 6061 material, particularly where repeated repairs are required. Although other aluminum weld rods show promise none are readily available for practical application.

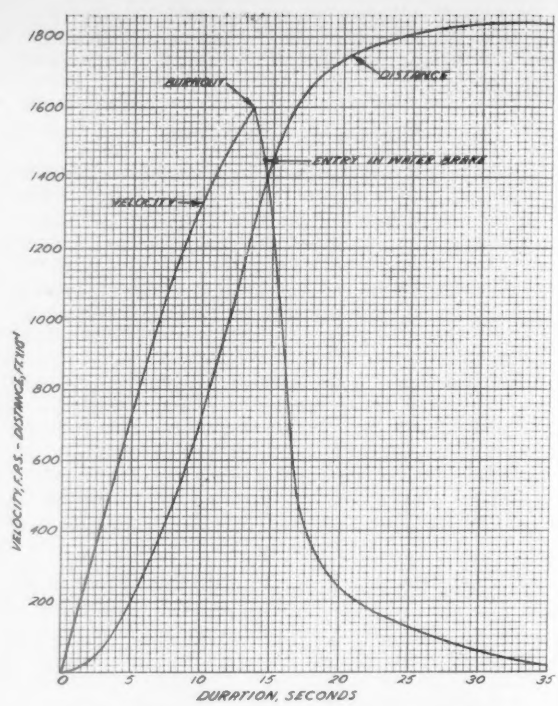

Fig. 3 Typical sled trajectory velocity and distance

Fig. 4 Drag prediction curve

Initial manufacturing efforts were very encouraging. The first four tanks were completed, proof-tested, and placed in service with satisfactory results. Subsequently, failures and difficulties were encountered, and several tanks were damaged during proof tests. The failures during proof tests, and one deliberate burst test, indicated the critical areas to be in the longitudinal seam welds and further indicated that the internal stiffening rings could induce propagating-type defects. This information was used as the basis for a design change which involved removal of the internal stiffening rings and modification of the baffle mountings. The experience on the aluminum-tank program indicates that, to meet the design requirements with normal design safety factors, allowance must be made for about a 15 to 20 per cent loss of tanks during manufacture. Allowance will be made until fabrication techniques can be improved to keep pace with design and laboratory test criteria.

Because of the broad background of experience in fabricating pressure vessels made of 4130 steel, fewer difficulties were encountered during the manufacture of the gas tanks. With the exception of the requirement of meeting rather close tolerances in axial alignment, which necessitated close control of the heat-treating processes, the tanks for the AJ10-28 and AJ10-36 sleds were readily produced. The gas tanks are about 13 ft long (Fig. 1) and form the main load-bearing members of the sled structure. The AJ10-33 sled presented similar problems, with the significant addition of greater length. This increased length—about 19 ft over-all—and the attendant alignment problem necessitated a basic design change. A flanged, bolted joint was developed for the mid-section of the gas tanks to permit adjustments for axial deviations and to minimize heat-treatment problems resulting from limited oven capacity.

The design and fabrication phases for the components of the rocket system were simplified by the use of articles previously proved. Minor revisions were made to suit the components to this particular application, and static and dynamic tests revealed the necessity for additional modifications, such as the relocation of bleed points, the adjustment of gas-pressure control systems and the de-sensitizing of electrical control system relays. Availabile information and previous experience with other track operations were used as the bases for the slipper designs. Experience indicates that, for sled weights between 4000 and 12,000 lb, the current $\frac{1}{8}$-in. 304 SS lining in a $\frac{1}{4}$-in. 4130 outer slipper is not entirely satisfactory. Other materials are being investigated and complete redesign of the slippers is being considered.

As stated previously, it was believed that the reliability and confidence level of the thrust chamber propellant combination had been adequately demonstrated on other programs, and that evaluation of the particular system would be minimized. The effects of the particular structure and the influence of line strength on combustion stability were examined on the basis of similar systems and of known parameters; it was concluded that operation of the system would be satisfactory. The basic design criteria for the rocket included consideration of, and provisions for, adequate instrumentation to monitor both the rocket system and sled environment parameters. All instrumentation was selected to be compatible with existing telemetry systems. Typical functions monitored are gas tank pressure, regulator pilot pressure, regulator outlet pressure, propellant tank pressures, propellant feed-line pressures, fuel flow rate, thrust chamber pressure, thrust chamber valve position, thrust chamber pressure switch actuation and control circuit conditions.

The pneumatic, hydraulic and electrical control systems are all designed to meet requirements of simplicity, reliability and rapid response. Preliminary system evaluations were made on mockup setups. Provision is made to permit propellant servicing without electrical power on the sled circuits and to effect safe shutdown within 0.3 sec of signal under both command and automatic signal conditions. The configuration of actuation gas circuits is such that any loss of gas pressure automatically activates the rocket shutdown system, closing the thrust chamber valve and opening the propellant tank vents. Operation of the thrust chamber valve is controlled by a pneumatic-hydraulic circuit providing positive action at a predetermined rate.

The rocket system is basically operated as follows: A solenoid pilot valve admits pilot gas at a pre-set pressure to the dome of the main gas regulator at a nominal rate of 200 psi per sec. The main gas regulator pressurizes the propellant tanks at about 200 psi per sec. A pressure switch senses the tank pressure rise and signals the thrust-chamber valve to open. The propellants, IRFNA and AN-FA, are admitted to the thrust chamber and ignite spontaneously. JP-X sustaining fuel follows the AN-FA after breaking of the separation diaphragm, continuing combustion until shutdown is signaled by propellant exhaustion or command.

Static and Dynamic Testing

Test plans and programs for the sleds were based upon the general applicable specifications and the specific requirements of the particular end use for the sleds.

Prior to initiation of static firing tests, thorough flow checks were made of the various gas and liquid circuits of the sleds to verify the accuracy of calculated pressure drops. The results of these tests were used to balance the system for nominal rated mixture ratio under static conditions. Sharp-edged orifices are used for controlling propellant mixture ratio. Because of the differences in the sled configurations, various locations and pressure-drop values are used in the different models.

Since weight, and consequently the high pressure gas tank sizes and pressure ratings, are important, orifices have been used in some of the sleds to hold the required weight flow of gas at the proper value for each propellant. This permits the use of a common, main gas regulator system with resulting simplicity and a minimum number of components.

Final leakage, functional and electrical checks are conducted prior to installation of the sled at the static test stand. Both the soaping method and the halogen detection method are utilized in the leakage tests to insure that all pressure systems are satisfactory. The functional tests include setting and checking of control and pilot gas regulators, operation and timing of the thrust chamber valve and operation of all other pilot and control valves. After satisfactory completion of the functional checks, the electrical system, including the sequence unit and harness, is tested using a checkout unit to simulate the various conditions of "load," "stand-by," "fire" and "shutdown." This series of tests verifies correct operation of the various relays, timers and pressure switches which comprise the control system. The circuits are designed and electrically interlocked to prevent power reaching the firing circuit unless the relays and pressure switches are in the ready condition, and also to signal shutdown if power is lost for any reason.

The installation of a liquid rocket sled for the initial checkout firing test involves the following general steps: Attaching the thrust take-out structure on the stand to the sled, plumbing and wiring the instrumentation, wiring the test control circuits to the sled, adjusting the safety deluge system, final leakage checking of test connections, final electrical checking and servicing. Both the AJ10-28 and AJ10-36 sleds were mounted so that axial loads were transmitted to the stand through the forward bulkhead and vertical loads were taken out through both the main forward and main aft bulkheads. The main axial thrust take-out area on the AJ10-33 sled is located aft at the water brake. Vertical loads are transmitted through the slipper supports. Pressure transducers were plumbed with minimum-length, $\frac{1}{4}$-in. tubing leading to the applicable pressure taps provided. Thermocouples, accelerometers and valve trace potentiometers were installed as required. The electrical instrumentation connections were made with cables from the stand terminal patch board to the transducers and thermocouples, and directly to the harness instrumentation plug, in the case of switch traces for relay and pressure switch monitoring circuits. The test-stand deluge system, a high capacity, remotely controlled water supply, was plumbed and positioned for adequate coverage of the vehicle. The leakage and electrical tests are conducted to insure that all test connections are satisfactory and that firing controls are operating properly.

Servicing for static tests is accomplished by pumping the oxidizer and sustaining fuel into the tanks through the sled servicing connections. Rigid tubing is connected to the sleds and then terminated at the edge of the stand, where either trailers or drum containers are used as the source. The pressure source is provided by either centrifugal or positive displacement pumps. Return lines that control the level to which the tanks are filled are routed to convenient bleed dis-

posal locations. The nominal tank ullage for rated duration is 5 per cent. The mixture of 30/70 aniline and furfuryl alcohol used for the starting fuel is obtained from a small tank, elevated to produce sufficient head pressure. Approximate times required for servicing are 15 min for the starting fuel, 10 min for the main fuel and 20 min for the oxidizer. Jumper connections are made to the gas actuation circuits for the vent valve and the thrust chamber valve in order to positively position the valves without the requirement for electrical power or gas pressure on the sled.

The first checkout test is usually a 4 to 5 sec firing to evaluate general operation and to adjust mixture ratio and thrust level. If tank pressures are maintained at those to be used on dynamic tests, the static thrust level is lower than the predicted dynamic level, because of the absence of acceleration head effects on the propellants.

A test plan similar to that of Table 1 is then followed. During checkout, adjustments are made in pressure rise rates, pressure switch settings, timers and orifice sizes. The shakedown tests are then initiated and the peripheral areas of operation are evaluated. Deliberate off-mixture conditions are imposed, the thrust chamber valve is operated at abnormal rates, propellant tank ullages are varied, power loss and other malfunction conditions are simulated—all to determine operating characteristics and safety. The results of these tests to date have been entirely satisfactory, and the anticipated reliability of the rocket system has been realized. Full thrust is attained in about 0.1 sec after initial ignition. The overshoot in chamber pressure at the start is less than 20 per cent of the rated pressure, steady-state oscillations in chamber pressure are less than ± 5 per cent of the rated pressure, and shutdown is completed within 0.3 sec after any type of signal, command or malfunction. Minor afterburning occurs for 1 to 2 min and minor fuming for 5 to 10 min after shutdown. No carbonaceous deposits are formed and no purge is utilized. In cases where the sled is not operated to full duration, propellants are removed from the tanks after the test, and the injector manifold is drained.

Table 1 outlines a representative, static, preliminary flight rating (PFR) test program which evaluates starts, steady-state operation, shutdown, malfunction, safety limit and environmental conditions. Static PFR tests of the AJ10-36 sled had already been initiated when it was decided to change the starting sequence from a pre-pressurized system to a transient system. The advantage of the transient system, in terms of reduced tank working pressure, can be seen when it is observed that the characteristics of the main gas regulators in use resulted in pre-pressurized tank pressures of 50 to 100 psi higher than normal firing pressures. The lower operating tank pressure was considered especially desirable to increase the margin of safety between tank operating and design burst pressures. The pre-pressurized start with its separate arming cycle (admitting gas pressure to propellant tanks) and firing cycle (opening the thrust chamber valve) was changed to the transient start by combining the cycles. Gas pressure is admitted to the propellant tanks at the same 200 psi/sec rate by the firing-switch signal, and the signal is sent to the thrust chamber valve at some predetermined tank pressure sensed by a pressure switch. Test firings were conducted with pressure-switch settings over a band from 450 to 525 psi and with tank ullages of 5 and 50 per cent to determine the system sensitivity. The 525-psi switch was selected for service; however, safe operation was obtained at all settings.

For convenience, the development and static PFR tests of the AJ10-36 system were conducted on a mockup sled, and only adjustment and acceptence tests were performed with the first deliverable vehicle. An abbreviated static-test program was conducted on the similar AJ10-28 sled, and the dynamic-test program on it was initiated while work proceeded on the AJ10-36 static-test vehicle. Static tests of the AJ10-33 sled will begin in the near future.

A typical dynamic-test program is outlined in Table 2.

Table 1 Typical static-test program

	Number of tests
Checkout	
Check system operation; adjust to optimum conditions	2–5
Shakedown	
Rated conditions	2
High mixture ratio	2
Low mixture ratio	2
Fast thrust chamber valve operation	2
Slow thrust chamber valve operation	2
Shutdown during starting transient	2
Loss of electrical power	2
Loss of pressurizing gas	2
Rated thrust, serviced for 50% duration	2
Preliminary flight rating	
Rated conditions	1
Maximum thrust	1
High mixture ratio	1
Low mixture ratio	1
Fast thrust chamber valve operation	1
Slow thrust chamber valve operation	1
Loss of electrical power	1
Loss of pressurizing gas	1
High temperature environment	1
Low temperature environment	1

Combined with this PFRT program is a nose-environment study program utilizing accelerometers and velocity transducers. High and low frequency telemetering transmitters are provided for rocket and environmental monitoring transmissions. The dynamic-test program is intended to demonstrate safe and satisfactory operation of the liquid rocket sled under dynamic conditions. Again the peripheral conditions of mixture ratio, valve timing and deliberate malfunctions are tested to show the system adequacy under these conditions. Seventy-one dynamic tests of AJ10-28 and AJ10-36 sleds have been completed with over-all satisfactory results. The propellant tank baffling was designed for dynamic operation, and propellant exhaustion tests were made only on the track. The rocket shutdown system functioned well under these conditions. The primary problems encountered during the dynamic-test phase have been the obtaining of high quality telemetry records and excessive slipper wear. Telemetry problems are being resolved by improved wiring and calibration techniques, but the slipper problem is more difficult. The present, formed, 304 stainless steel, $\frac{1}{8}$-in. gage liner with a 4130 $\frac{1}{4}$-in. outer case does not appear satisfactory for maximum velocity conditions on the AJ10-36 sled. Excessive wear is occurring at the higher velocities. Solutions involving thicker lining, shifted pivot location, hard facing material, aluminum bronze, cooling fins or complete redesign are being considered.

Rocket servicing procedures for dynamic testing are similar to those for static tests except that quick disconnect nozzles are used for the oxidizer fill-and-return lines to the trailer, permitting the use of a rapid-filling, closed-circuit system. The times required for the operations are similar to those noted for static testing. The service life of parts is satisfactory thus far; for example, only one thrust-chamber valve replacement was required in 12 track tests. Even with the scheduling and operational problems accompanying a generally heavy work load, it has been possible to maintain a good track testing rate. The limiting time factors have been those of servicing and readying the nose environmental instrumentation. Since moderately large numbers of functions are being monitored, considerable follow-up, test record evaluation, data reduction, calibration and transducer relocation between tests are required. These tasks represent time factors which are not easily reduced.

Table 2 Typical dynamic-test program

	Number of tests
Checkout	
Loss of electrical power (subsonic)	1
Shakedown	
Rated thrust, serviced for 50% duration	2
Maximum thrust	2
Loss of oxidizer supply	1
Preliminary flight rating	
Rated thrust, full duration	2
Loss of electrical power	2
Loss of pressurizing gas	2
High mixture ratio	1
Low mixture ratio	1
Fast thrust chamber valve operation	1
Slow thrust chamber valve operation	1
Thrust chamber pressure-switch failure	2
Vibration environment	
Conducted during PFR tests	

Instrumentation

The basic system for monitoring the liquid rocket operation during static tests used a direct wire from the transducer to the coupling unit and to the end instruments. Wiancko, Aerojet and Statham pressure transducers, Statham accelerometers, iron-constantan thermocouples and variable-resistance potentiometers are used on the test sled. Wires are routed from these to the stand terminal patch board, through conventional stand conduit wiring to the instrumentation-room patch panel, into Wiancko or Consolidated coupling units, as required, and from there to oscillographs or direct-reading instruments. All functions are recorded on two different instruments, facilities permitting, and in some instances duplicate transducers are used. High response galvanometers are used in the recording oscillographs. Accurate, slide-wire, direct-reading, strip-chart instruments are employed for tank pressures, chamber pressures and flow rates to permit monitoring the rocket operation during the test firing. Calibration of the pressure transducers in these systems is accomplished by applying known pressures—from a hydraulic table using standard weights to produce the pressure—to the transducers on the test vehicle, and recording the signal values at the end instrument. This method insures evaluation of the system as used during the test and eliminates errors often introduced by methods which involve special, calibration electrical links. Reduction of the records gathered from the static tests produced data with the accuracy expected for this type of instrumentation system. Excellent correlation was obtained with previous data gathered and averaged during the more than 600 tests on this and similar thrust chambers.

For instrumenting the dynamic tests, transducers had to be selected that were compatible with existing telemetry systems. Statham strain-gage transducers and Raymond Rosen transmitters were installed on the AJ10-36 sled. Provisons were made for 12 channels of liquid rocket parameters and for 12 channels of nose environment transmissions. The transducers for this system are bench-calibrated, after which the electrical circuits are checked against known electrical inputs. The rocket data, although showing considerable scatter, indicate satisfactory results and would fall within the wider accuracy band known to be inherent with available telemetry systems. Data are received at the ground station and recorded on magnetic tape. Some functions are simultaneously recorded on pen-type, direct-reading instruments for quick-look data after the test. The usual analog presentation of the tape data is made by playing back the tape into recording oscillographs. As on other programs, the analysis of the environmental velocity data and the acceleration transducer data is difficult. The natural frequencies of the transducers, recorders, galvanometers and nose section must be considered when reducing the recorded data. Correlation of known forces of thrust and velocity (as shown by the track velocity indications) with certain of the environmental transducers provides an excellent check. This correlation also gives information which can be applied to the data reduction problem in general. The selection of the true acceleration amplitudes and frequencies becomes a process of selective rejection of noise, harmonics and other misleading values. Other factors such as slipper wear are indicative of actual forces and help to point out the proper method of record interpretation. Considering the additional reduction in accuracy due to the limitations of this type of analysis, the results are somewhat lacking. However, these data, particularly when they may be considered for a large number of tests, are significant and do establish the environment within a certain band of values.

Conclusions

(a) Major design objectives have been achieved; liquid rocket sleds have been successfully designed, fabricated, tested and operated. (b) The systems are trouble-free, reliable and capable of repeated rapid operation. (c) The acceleration conditions produced can be used for the important nose-section payload tests.

Redstone Arsenal Ballistic Ramp

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THIS paper outlines what the Rocket Development Laboratory at Redstone Arsenal has done in development and testing on the ballistic ramp and what can be done to develop test techniques on a relatively inexpensive track.

The Redstone ballistic ramp came into being in 1955 when a construction contract was let for the sum of $150,000. This contract covered the cost of erecting a dual rail track 600 ft long and construction of an instrument building at the breech end of the track. The track itself was inclined at an angle of 3 deg with the horizontal to eliminate ground effect on radar instrumentation and to facilitate camera instrumentation. Location of the track was such that the muzzle was 35 ft above ground level. No auxiliary buildings other than the instrument building were included in the contract. It was planned to use environmental facilities at a nearby range to service the track. The original contract specified that the rails be aligned to within $\pm\frac{1}{4}$ in. over the entire length of

Presented at the ARS Spring Meeting, Washington, D. C., April 4–6, 1957.

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track. Both track rails were welded at the joints in order to provide a substantially smooth continuous rail length. Vertical and lateral adjustments stations were located approximately 3 ft apart. Standard 60-lb railroad rail was used. After the contractor had completed his work, a test sled was fabricated and was hand run up the track as a rough check of track alignment prior to firing a test sled. Subsequent to this rough check a survey was made to check rail alignment. It was discovered that there was a small bow toward the muzzle end of the track and this was corrected.

Sled construction was aluminum; sled shoes were magnesium. Magnesium shoes were used since test work by the Naval Ordnance Test Station at Inyokern indicated that magnesium was one of the best materials for light sleds. Based on previous calculations the velocity reached by this sled should have been approximately 1000 fps, 500 ft down the track. Measured maximum velocity was 850 fps, 450 ft down the track.

A magnetic pickup system was used to measure time-distance and by differentiation obtained velocity-distance.

Since the first sled run was successful and since it was imperative to start firing air-to-air rockets for data, an accelerated track checkout program was necessary. In quick sequence (about one week) 12 sleds were run.

At the conclusion of this limited test sequence it was decided that the track was ready for use and on June 6, 1955, the first test rocket was launched at 15 deg elevation relative to the track. Launch velocity was 854 fps. Since that time 310 data runs have been completed with only a few isolated instances of failure. In one instance the sled propulsion unit was conditioned at a higher temperature than normal, and the booster motor failed; however, no damage was done to the track.

Sled designs have generally proved satisfactory on first firings with nothing but elementary stress analyses being computed. Undoubtedly all of our sleds are overdesigned. When we reach a state of the art where every ounce of material overweight imposes a penalty on test conditions, then a more refined sled design procedure will be used.

After the track had been in test use for four months we received a request for launch velocities of 1500 fps. We had previously achieved velocities of 1100 fps using two obsolete 5-in. HVAR's at propulsion units on a standard two-rail sled. It was felt that 1500 fps would require an approach other than brute force. Accordingly, a monorail sled design was fabricated. The original monorail sled (Type I) used standard shoes. A 5-in. HVAR was used as the propulsion unit. This sled, tested with its rocket payload, reached a velocity of 1274 fps at rocket launch.

In addition to an increase of launch speed there were four other objectives in the design and test of the monorail sled:

1 To achieve a more stable launching platform and thus decrease rocket dispersion errors caused by sled movements. In previous firings using a dual-rail sled, it was discovered that the dispersion of sled-launched rounds was somewhat greater than that of rounds launched from aircraft. This in itself was not serious enough to affect the over-all results of the tests, but indicated that steps should be taken at least to minimize extraneous sled motions. Static tests were conducted on dual-rail sleds to determine sled movement. It was discovered that cumulative tolerances added up to an elevation change of 9 mils that could be introduced by sled bounce. It was also discovered that it was possible for the launcher to be malaligned ± 5.5 mils horizontally due to random motions during travel. It was evident from dispersion data that all this motion was not being reflected directly in rocket dispersion; however, it was necessary to eliminate any possible source of dispersion not connected with the test rocket.

2 To establish aerodynamic control of the sled such that it would dive quickly after leaving the track to avoid blocking Doppler radar instrumentation. The most suitable position for our Doppler radar is directly behind the track, and a tumbling sled, because of its larger size, overrides the signal from the test item.

3 To produce a more economical sled than the dual-rail.

4 To provide experimental data for further extension of track-launching velocities to a possible secondary objective of 2500 fps.

During its free flight after leaving the track the original Type I sled had flown for several hundred feet without tumbling, apparently stabilized by its fore-and-aft braces. In an attempt to capitalize on this characteristic, the braces on the Type II sled were canted downward to "fly" the sled out of the radar beam.

Six tests of the Type II sled were made, two with live rockets. Both rocket firings were made at a launcher elevation of 15 deg. Launch velocities were approximately 1200 fps. The "wings" did not function as anticipated and the sleds tumbled. The two live firings were conducted with Type 310 stainless steel shims in the shoes to reduce track shoe clearances to 0.050 in. vertical and 0.060 in. horizontal. A final Type II monorail sled was fabricated equipped with close-fitting (0.030 in. vertical and 0.043 in. horizontal) magnesium shoes. The maximum sled roll (cant) that could have been introduced by various shoes was:

Shoe type	Maximum roll (mils)
1. Standard	180
2. Steel shim	45–54
3. Close-fitting magnesium	29

Study of magnesium deposits left on the rail by close-fitting magnesium shoes indicated that the sled did not roll. This was further substantiated by the position of the ignition knives at second-stage ignition. Ignition screens were sliced cleanly and the cuts were equidistant above the rail. The combination of aerodynamic loading (slanted wings) and close-fitting shoes appeared to have eliminated the tendency of previous sleds to bounce.

The tests of sled designs continued toward satisfying all of the afore-mentioned objectives. At this point we felt that we had a sled system capable of carrying the test item to 1250 fps and launching it at angles relative to the track up to 15 deg, and that we had cut down on sled motions at launch. However, the problem of obtaining radar velocimeter data, i.e., the problem of diving the sled out of the way, was only partially solved.

The velocity problem at this point appeared to be one of obtaining a more suitable booster motor, one with a shorter burning time and a higher specific impulse. Shopping around uncovered a motor that satisfied the second of these requirements. Lack of funds prohibited purchase of new motors and the high impulse boosters discovered were fortunately surplus. The motors weighed one quarter as much as the HVAR and had about half the thrust.

Complete sled weight, including payload was 52 lb compared to 156 lb for the HVAR-propelled Type II sled. Diving "wings" were included in the design since it was felt that the lighter mass (approximately 28 lb after rocket launch) might insure success of our "wings." Two Type III sleds were fired, on June 1 and 8, 1956. The booster on the first sled burned through near the head end, but in spite of this the launch velocity was 1386 fps. The second sled functioned satisfactorily and reached a rocket launch velocity of 1506 fps. Both sleds dived out of the radar beam. For the first time in our tests a good radar velocity-time plot was obtained from a zero degree launch. Based on these firings it was decided that 1500 fps launchings were feasible with an 11-lb payload and that the Type III sled would be suitable for this type firing.

Although it was evident that even at these velocities the booster was burning beyond the track, a further speed test was

conducted using a monorail sled with two boosters, Type IV. Two sleds were launched and reached 1550 fps at rocket ignition and approximately 1730 fps at the end of the track. Neither rocket was launched until the sled had traveled 200 to 250 ft past the end of the track. It appears then that, with the present booster motors, 42-lb sled and the particular rocket tested, 1500–1700 fps is the top speed. For the 600-ft track to reach higher velocities, a booster designed for track operations is needed. Since very little difficulty with shoe erosion or sled malfunctions has occurred, it is felt that with a suitably designed booster no troubles will be encountered at higher velocities. All the tests previously described were conducted while the track was in use for project test and represent only a small test effort on our part.

The Capabilities of the Holloman Track

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Introduction

THE complexity of present and future weapon systems has created the need for more refined test facilities. Only recently has it been recognized that large-scale captive testing is essential, and its addition to the development cycle, costly as it may be, actually shortens this cycle and reduces development costs.

As an example, consider the launching of a guided missile. An aircraft-type structure which duplicates the shape of a missile is filled with a multiplicity of components and working mechanisms, blasted into the sky with powerful propellants, and it is hoped that all components will function properly. When one component fails under the take-off blast it is only in rare cases that the defective component can be clearly identified in the resulting wreckage.

Hence, new methods must be devised to give assurance that the specific item is reliable, and that all components will perform together as expected under actual flying conditions before being actually launched into the air for the first time. The requirements for a test facility to do such a complex job are ideally fulfilled by a high speed track.

Description of the Track Facility

General Information

The Holloman track is located on the floor of the Tularosa Basin of southern New Mexico, at an average elevation of about 4100 ft above mean sea level. The general orientation of the track is south to north. The profile of the track shows a rise of 1 ft per 1000 ft.

The track consists of a U-shaped, reinforced concrete foundation supporting the 171-lb per yard crane rails, fitted with alignment-anchor fixtures. It is 35,000 ft long, consisting of 5000 ft of previously existing track and 30,000 ft of newly constructed track.

In cross section, the U-shaped foundation is $9\frac{1}{2}$ ft wide and 5 ft high, and provides a water trough 60 in. wide and 14 in. deep along its entire length. The volume of water, for braking, can be varied by the insertion of masonite dams at 10-ft intervals. Varying the height of these dams permits the deceleration of test vehicles to be programmed within close limits.

Design Criteria

The track, planned by Holloman Air Development Center, was designed and constructed by the Corps of Engineers, Albuquerque District. It resists the following loads produced by the moving vehicle: (a) Vertical downloads of 70 kips per slipper, (b) vertical uploads of 25 kips per slipper and (c) lateral loads of 40 kips per slipper on any two slippers.

For design purposes it is assumed that a typical test vehicle will be equipped with four slippers, two in front and two in the rear, each 2 ft long and spaced, front to rear, on 12-ft centers.

The track gage is 7 ft between center lines of rail tops. The 39-ft rails were forge-welded, in a field shop at the site, into four continuous rail sections—three of them 10,000 ft in length and the fourth 5000 ft. To offset expansion at high ambient temperatures the rail sections were prestressed by hydraulic jacks before tie-down to a length calculated to produce zero tension at 120 F. The exact magnitude of stress initially imposed on the rails by tension varies with the actual rail temperature at the time of tensioning.

The rails are anchored to the concrete girder at 52-in. intervals by fixtures which permit vertical and lateral alignment in addition to holding down the rail. The rails are further supported by an asphalt ballast, interrupted every 52 in. by the alignment fixtures to provide suitable damping for the rail proper, so that no wave propagation resulting in stress multiplication for the girder may develop.

The concrete girder must resist dynamic loads imposed by the test vehicle moving at supersonic speeds on the track. Hence, the design is based on theory for "ultimate design," i.e., on the action of reinforcing steel and concrete beyond the elastic range where stress is no longer proportional to strain.

The loadings under consideration for the track girder are either of the impact type or of extremely short duration. It was therefore considered conservative to use ultimate stress for concrete compression and yield stress for mild steel in designing against moving slipper loads.

Dynamic Considerations

An analysis has been made of the behavior of the track under moving loads. However, it must be kept in mind that the results are based on assumptions and estimates which are difficult to confirm without extensive field tests. Such tests are now in progress.

According to G. W. Housner (1)[2] the design of the track may be safely based on the criterion that the moments produced by dynamic forces will not exceed twice those produced by equal static loads. The analysis of the girder shows that it is capable of resisting a maximum vertical momentum of about 320 ft kips. Assuming that the moment is imposed by two reactions spaced 12 ft apart between front and rear slipper, the concrete girder will be capable of supporting 40 kip downward slipper loads traveling at critical velocity. Upward slipper loads of 25 kip moving at critical velocity will

Presented at the ARS Spring Meeting, Washington, D. C., April 4-6, 1957.

[1] Technical Director of Research & Development. Mem. ARS.

[2] Numbers in parentheses indicate References at end of paper.

produce concrete and steel stresses of 192 psi and 1930 psi respectively.

Construction Procedures

It is important that the foundation of the concrete girder is homogeneous over its entire length. Even though the floor of the Tularosa Basin is unusually flat, some cuts and fills were necessary in laying out the track.

To position the girder within 0.25 in. required extreme care during fill operations and fills were kept to a minimum. The track follows the terrain with a radius of curvature of not less than 1 million ft, rather than a straight line. Tests on the degree of compaction showed that compaction between 95 and 98 per cent was actually achieved. It may be noted that settlements of as little as 0.25 in. will throw that portion of the track out of alignment tolerance.

A 10-in. concrete foundation was designed to serve not only as part of the track base but also to act as a firm mounting for steel forms, used to shape the main girder, and for holding them to 0.25 in. tolerance.

The steel forms, in addition to shaping the concrete foundation within the required tolerance, also acted as templates for the setting of the alignment fixtures. During the pouring operation approximately 700 ft of foundation were poured in an eight-hour shift.

The rails were forge-welded from standard 39-ft sections of 171-lb crane rail, rolled by Bethlehem Steel Corp. Special welding equipment was required to produce rail-butt alignment within the tolerance allowed. Cutting, welding, heat treating and grinding were done with special tools in six steps. About 8 min were required for one complete welding operation.

Final Alignment

As stated, the track follows the terrain with a radius of curvature of not less than 1 million ft. This requires that the rail must be aligned to very close tolerances by continuous survey. A first-order base line with a probable error of not more than one part in 2 million is provided as a reference line. From this base line the top and inside faces of the master rail are aligned to within ± 0.005 in. The other rail is aligned to the master rail to within ± 0.01 in. This alignment accuracy applies to that portion of the rail directly over the alignment fixture. Small misalignments that may exist between the fixtures result in high frequency vibrations which rarely are transmitted from the slippers to the main parts of the sled and are not considered serious. More serious are vibrations transmitted to the sled structure by misalignments several hundred feet in length.

Alignment requirements must be based on the predetermined value for the allowable maximum transverse acceleration at a given velocity, i.e., on the curvature of the rail. With $1/\rho$ the curvature of the trajectory of the center of gravity and v the velocity of the rocket sled, the transverse acceleration is

$$a_t = \frac{v^2}{\rho}$$

Postulating that at a speed of Mach 5 the transverse acceleration shall not exceed 1 g, the radius of curvature must be at least 940,000 ft, which is slightly less than the specified radius of curvature of 1 million ft.

When the load is traveling at near critical velocity ($v/v_{cr} \cong 1$) the maximum deflections and moments may appreciably exceed maximum deflections for static loads. The effect of damping, however, tends to reduce the deflections and bending moments. Damping is produced by energy losses due to stresses within the beam, stressing of the soil underneath the beam, and propagation of stresses through the ground in the form of seismic waves.

Critical Velocity

The critical velocity in the beam for the Holloman track was computed by G. W. Housner according to a method developed by J. T. Kenny Jr. (2). The critical velocity depends on the modulus of elasticity E, the moment of inertia I, the mass of the concrete beam ρ, and the foundation stiffness of the beam k.

None of these quantities can be determined very accurately for the beam under consideration. The modulus of elasticity is taken to be $E = 4.32 \times 10^8$ lb/ft² and the moment of inertia for the concrete section to be $I = 16.7$ ft⁴. To determine the mass of the beam it was assumed that approximately 2000 lb/ft of soil will move with the beam of 3700 lb/ft dead weight, giving a total mass of the beam of $\rho = 177$ slug/ft. The soil under the track deflects 0.06 in. under a bearing load of 3000 lb/ft², giving a foundation stiffness of $k = 6 \times 10^6$ lb per ft/ft.

The critical velocity of the track is given by

$$v_{cr} = \sqrt[4]{4kEI/\rho^2}$$

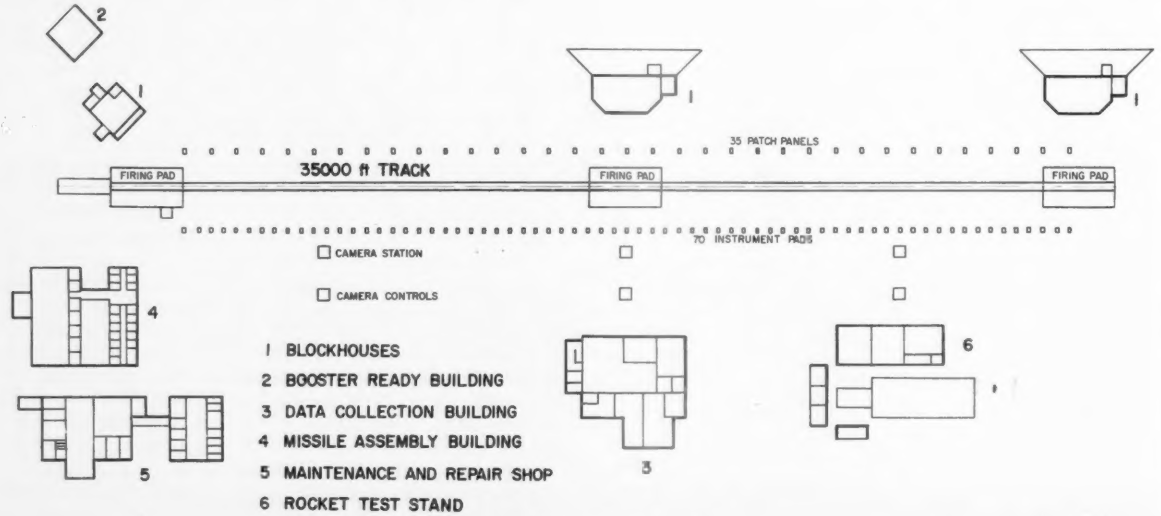

Fig. 1 Holloman track complex

With the above numerical values

$$v_{cr} = 1550 \text{ fps}$$

The critical damping is

$$c_{cr} = 2\sqrt{k\rho} = 62\,000 \frac{\text{lb sec}}{\text{ft}}$$

The true values of critical velocity and of damping may be determined only by extensive tests.

For speeds in excess of the critical speed the load must be accelerated through the critical velocity. In order to measure the stresses in the beam and to determine the actual critical velocity, a 4000-ft section of the track between stations 15,500 and 19,500 is instrumented with strain gages placed at 100-ft intervals.

Support Facilities

Support facilities are being provided in order to extend the capabilities of the track and to reduce the time between runs. In the past the utility of tracks has frequently been hindered by the lack of facilities necessary for the preparation, modification and maintenance of rocket sleds, for check-out procedures of instrumentation and test items prior to a test run, and for proof-testing of rocket engines. In fact, unless such facilities exist at the track site, maximum use of the high speed track cannot be made. Fig. 1 shows the support facilities which have been included in the Holloman track complex. These facilities consist of:

1 Three blockhouses, one each at the south and north end of the track, and one halfway between. Each blockhouse is equipped with a complete firing circuit and rocket sleds may be fired from any one of them.

2 A booster-ready building near the south end of the track, to permit the conditioning of the boosters for optimum performance prior to their use.

3 A data-collection building connected with the blockhouses, firing pads and instrumentation sites is the heart of the extensive instrumentation network of hard lines, coaxial cables and radio links; the building facilitates communications and data collection.

4 A missile-assembly building in which the contractors match the test items to the rocket sleds and check the instrumentation prior to a sled run.

5 A maintenance and repair shop for the large number of rocket sleds used at the track.

6 A rocket test stand for horizontal burning of rocket sled engines capable of withstanding 1 million lb thrust, for proof-testing and calibration of liquid and solid propellant rocket engines to be used on the track.

Track Performance

Sled Ballistics

Sled ballistics deals with the motion of rocket sleds and provides a means of computing sled velocities from the known characteristics of the propulsion system and of the sled.

In general a ballistic trajectory of a rocket sled on the track consists of four phases: (a) An acceleration phase during which the sled is accelerated for a required period of time or to a required speed, (b) a sustained constant speed phase, (c) a free run or coasting phase and (d) a deceleration phase. Depending on the test objective, any one of the four phases may be more important than the other phases and may be programmed. Fig. 2 presents a number of typical trajectories which are conceivable on the 35,000-ft track.

The actual trajectories, however, which may be attained are restricted by the performance of available propulsion systems and the aerodynamic design characteristics of the rocket sled used

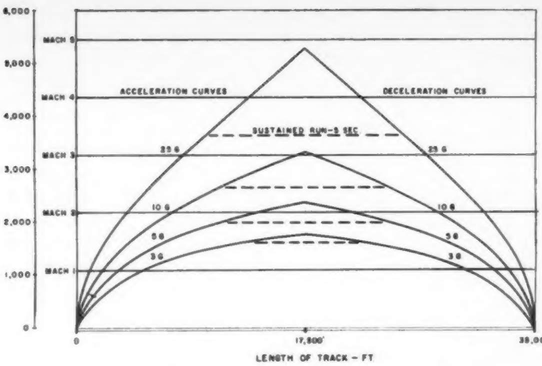

Fig. 2 Ballistic trajectories of rocket sled

The ballistics of rocket sleds and the resulting equations have been treated extensively (3, 4). A number of assumptions must be made to arrive at practical solutions for the motion of a rocket sled. Since we are proceeding into an unknown area, the actual performance limitations will be known only after the soundness of the assumptions have been proved in actual tests.

We would not have built a 35,000-ft track without the assurance that a specified minimum performance could be attained. With available propulsion systems and sled designs it is possible to attain linear accelerations up to 100 g, velocities in excess of 3000 fps and decelerations up to 150 g for recoverable test vehicles.

In order to exceed these values it will be necessary to develop propulsion systems giving approximately 60,000 lb thrust per sq ft of frontal area, and having rocket indices of 180 lb sec/lb and total impulses between 1 and 10 million lb sec. Such propulsion systems may use either liquid or solid propellants. Sled designs will have to meet specific test requirements of the project for which they are to be built.

Great effort is being made to investigate the effect of ground interference on the ultimate speed of rocket sleds. The problems encountered in this area include choking of the air flow underneath the sled, lift forces and interference drag of bracings and support struts, sled body and water scoop. Choking of the flow underneath the sled causes undesirable pressure distributions resulting in large overturning moments. Lift forces cause the sled to fly rather than to ride on the top of the rail. Some lift on the sled is desired, but it must be controlled. The ideal sled configuration would have just enough lift to carry the sled weight and to relieve the slipper loads.

Determining the ultimate speed which may be attained with a rocket sled is the mass ratio of the vehicle: that is, the ratio μ of the total mass of the sled at the start M_0 to the mass of the sled after burnout M.

Assuming values for the thrust T, of the propulsion system, the air drag coefficient c_d, including ground interference, and the frontal area A, of the vehicle, a terminal velocity for the sled may be computed

$$v_T = \sqrt{2T/c_d\rho A}$$

where ρ is the density of the ambient air, which is constant at the track tests.

The actual velocity which can be attained depends then only on the mass ratio $\mu = M_0/M$ and the specific impulse I_{sp} of the propellant, viz.

$$v = v_T \frac{\mu^k - 1}{\mu^k + 1}$$

where $k = 2g\ I_{sp}/v_T$.

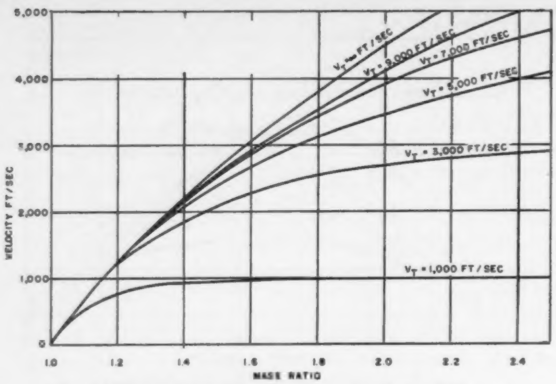

Fig. 3 Rocket sled velocity vs. mass ratio for different terminal velocities—velocity at start, $v_0 = 0$

A plot of the velocity as a function of the mass ratio, as proposed by H. Schwinge, is presented in Fig. 3. This plot shows the actual speeds which may be attained with a rocket sled. Once a powerplant is selected, the terminal velocity may be easily computed. To reach actual velocities of, say, 4000 fps, mass ratios of about 2.2 and terminal velocities of 7000 fps must be accomplished.

The mass ratio of present rocket sleds is much smaller and a radical change from present sled design concepts is necessary if optimum performance is to be realized.

The drag coefficient c_d of a complex body such as a sled, moving near the ground with supersonic speeds, is not very well known. We expect that c_d values of less than 2 will be feasible at speeds of Mach 1.5 and above. Only extensive investigations of ground interference can provide actual data of this important parameter.

The maximum velocity of a rocket sled with given mass ratio and given specific impulse is obviously reached when the terminal velocity approaches infinity, denoting either infinite thrust or zero drag.

Sled ballistics also includes the problem of friction and wear at the contact surface between the slipper and the rail. For the anticipated speeds in excess of 2000 fps and distances of 7 miles this problem has no precedent. Even though most of the slipper wear which is presently being observed at high speeds during long runs may be caused by uncontrolled moments and excessive lift, there still remains a real problem of wear.

This problem has been studied extensively in recent years and some progress has been made. At Holloman, the conviction is that some kind of lubrication between slipper and rail is needed. Studies by M. E. Shank (5) indicate that hydrodynamic lubrication may be the solution to the problem; but such lubrication imposes severe operational limitations which will be difficult to overcome. Imperfect lubrication, solid lubricants or extreme pressure lubricants may also solve the problem, as shown by S. Kyropoulos (6). In the case of solid lubricants it will be necessary to treat the rail with a compound which will absorb the energy created by friction and, at the same time, will reduce wear.

Instrumentation

Technical information from track tests is collected by precision instrumentation.

1 *Velocity and Position Acquisition System.* This system measures the velocity and the position of the rocket sled as a function of time. Present equipment measures velocity to an accuracy of about 1 fps at 1000-fps velocity and positions to within 0.1 in. With an improved system now being installed on the Holloman track, the rocket sled carries a small light source which directs a beam into a light sensitive element. Plates spaced at precisely known distances along the track interrupt the light beam as the sled passes. The signal is telemetered to the data collection building for time correlation and recording. Higher accuracies up to within 1 part in 20,000 for velocity may be determined with special instrumentation now under development, using high accuracy data from a sled mounted accelerometer in conjunction with space time data as proposed by F. J. Beutler and L. L. Rauch (7).

2 *Telemetry System.* Extensive use is being made of telemetry between the moving sled and the data collection building. Two different systems are being used at Holloman. The frequency modulation (FM/FM) system receives transducer data in continuous form with an error of about ±3 per cent. This error can be reduced by automatic calibration to about ±1 per cent. The pulse code modulation (PCM) system which is now under procurement will permit accuracies of 99.9 per cent. The system has 32 channels, each with ten bits of information and a sampling rate of 750 cps.

3 *Data Reduction.* Extensive data reduction facilities are available at Holloman. Selected portions of the telemetry tapes will be programmed into a 1103A Remington Rand computer to obtain the results in tabular, plotted or punch card form.

4 *Timing and Programming System.* The Holloman track is being provided with a dependable time signal and a programmer to cause events to take place precisely at a predetermined time and in proper sequence. The timing device provides pulses from 1 pulse per 100,000 sec to 50,000 pulses per sec. Event pulses are transmitted through pre-set selector panels to the proper location via ground lines or radio links.

5 *Special Instrumentation.* Special instrumentation for the track is constantly being developed. As an example Holloman has under development an optical system capable of providing shadowgraph and Schlieren pictures of the flow around a test item moving on the track. The shadowgraph system, being developed by Edgerton, Germershausen and Grier, Inc., will permit flow pictures to be taken during daylight operation, using a scotchlite screen as a reflector.

The Potential of Track Testing

A study of the potential of the track as a development tool is necessary in order to delineate future testing possibilities.

Evidently, the need for track testing lies in the areas where (a) controlled or sustained linear acceleration is essential, (b) large or full-scale test items must be selected, (c) costly free-flight testing can be eliminated, (d) repeated testing of the recovered test item is needed and (e) high dynamic pressures are important.

Since high speed tracks have now been recognized as major development tools, the tests which have been successfully conducted in the past are expected to continue in the future. The completion of the 7-mile track at Holloman will remove limitations which have been previously imposed on a number of test programs.

Biophysical investigations of flight environments will be extended to higher speeds and higher dynamic pressures. Performance and reliability tests of escape systems will also be extended following the trend to higher aircraft speeds. Longer runs of constant speed can now be provided for testing the ejection of multiple escape devices.

Ballistic trajectories at high relative velocities as encountered with air-to-air missiles can be determined for single and multiple firings with great accuracy. Higher speeds can be provided for terminal ballistic testing for the evaluation of fuses and penetration effects.

Techniques for testing flutter and vibration characteristics of full-scale aircraft and missile structures on the track offer the design engineer test methods which will permit the deter-

mination of the correct conditions under which structural failure will occur, thus enabling the engineer to establish realistic margins of safety. Advanced methods are being developed, proposing nondestructive flutter test techniques which will permit determination of flutter speed and damping characteristics of an aerodynamic structure as a function of speed.

An important potential of track testing is its capability for proof-testing complete missiles and their components during acceleration and deceleration, as well as under vibration and shock conditions equal to or more severe than those anticipated in free flight. Such testing will detect weak components and inadequate designs prior to the release of the item to free-flight testing.

The performance of guidance and control systems for missiles may be repeatedly tested and calibrated on the track with full recovery of undamaged hardware and instrumentation. Such tests will be performed under realistic conditions of programmed acceleration, shock, vibration, and temperature extremes, such as experienced in free flight. Testing of this sort requires extreme accuracies of velocity and position measurements of the rocket sled. Environmental conditions at these tests should approach those encountered in free flight. Great effort must be made to improve the environmental conditions during the rocket sled run and to reduce those random accelerations due to propulsion, track misalignment and ground interference to a minimum. Appropriate methods for the testing of guidance systems are now being developed.

Such items as missile structures, pressure tanks, high-stressed joints and engine mounts may be tested on the track under realistic dynamic load conditions. The track test can simulate both the onset of acceleration and sustained linear accelerations as it will actually occur during missile flight. Very little has been done in this area and adequate test methods have not yet been developed.

Rocket engines may be tested under captive flight conditions on the track. Since the rates of flow through valves and connecting pipes must be accurately controlled, the control system must correct the increase of flow due to acceleration. Cold flow tests with rocket engines on the track may furnish the data for the correct valve settings.

Small components such as electron tubes, relays, gyros, fuel pumps and the like can be efficiently proof tested on the rocket sled in large numbers under environmental conditions more severe even than those expected in free-flight. The evaluation of such tests may be used to increase the reliability of the components.

Finally it should be emphasized that the track makes it possible prior to free flight to proof test full scale missiles for reliability and functional operation with all components functioning.

There are areas as yet untapped where track testing may prove extremely valuable. So far, test methods developed for track testing have, in most cases, been extremely successful. Great effort will be made to improve these methods. Along with increased test requirements goes the need for reducing the time between runs and for improving accuracy and handling and processing of test data.

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TRACK INSTRUMENTATION

Measurements of Vibration Environment in a Supersonic Liquid Propellant Rocket Sled

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Introduction

THIS paper is concerned with some preliminary investigations of vibration environment measured during sled runs at various positions within two sleds constructed by Aerojet-General Corp. The measurements were made by Aerojet at the Supersonic Naval Ordnance Research Track, China Lake, Calif., as part of a sled shake-down program. Measurements were confined to positions within the nose sections where specimen missile components are to be tested. Results of the investigations are intended to be used to evaluate component performance, to separate effects due to vibration and acceleration, to allow laboratory simulation of sled environment, and to establish sled environment for comparison with missile environment specifications.

A total of 18 dynamic tests were completed at the SNORT track from August to December 1956. The track utilizes

Presented at the ARS Spring Meeting, Washington, D. C., April 4–6, 1957.

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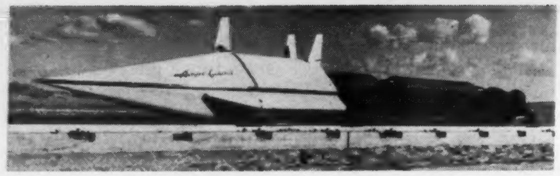

Fig. 1 Sled No. 1 on the Supersonic Naval Ordnance Research Track

50-ft spans of 171 lb per yd crane rails set at the standard railroad gage of 4 ft $8\frac{1}{2}$ in. and extends for 4.1 miles. Rails are bedded in heavy H-shaped reinforced-concrete continuous beam and are precision aligned to within 0.06 in. horizontally and 0.036 in. vertically. Fifteen runs were completed using Sled No. 1 and three runs using Sled No. 2. The nose sections enclosed telemetry, velocity measurement instrumentation and masses which simulated specimen components. Each sled was powered by an Aerojet liquid propellant rocket engine which produced a nominal thrust of 35,000 lb for durations of 3 to 11 sec. Total weight of each sled varied between 7000 and 8000 lb. The sled on the track is illustrated in Fig. 1. Typical trajectories are shown in Fig. 2.

The following sections will be concerned primarily with spectral analysis of the vibration data. The selected test run data presented are believed to be typically representative; however, selections were made on the basis of quality rather than content because large portions of the data are suspect for one reason or another. Studies are continuing in order to eliminate some troublesome uncertainties. It is hoped that it will eventually be possible to determine statistical variations resulting from different runs, changes in location of pickups in the sled and changes in operating conditions. In this way the characteristics of each rocket sled as a test vehicle may be more adequately defined.

Instrumentation

Twelve vibration measurements were made during each test run. Four types of accelerometers were used: Endevco 2201 ceramic crystal accelerometers for 5 to 2000 cps vibration, Giannini potentiometer and Statham strain gage accelerometers for low frequency vibration and Statham strain gage angular accelerometers for angular oscillations from 0 to 19 cps. Two clusters of three Endevco accelerometers were used in each run to measure linear accelerations in the three coordinate directions, while one cluster of three strain gage angular accelerometers was used to measure roll, pitch and yaw angular accelerations. One cluster of three potentiometer or strain gage accelerometers was used to detect low frequency linear acceleration.

During each test run, the 12 vibration measurements were transmitted via two 12-channel RDB standard FM/FM Raymond Rosen telemeters. Subcarrier channels A, C and E (22, 40 and 70 kc) were used in each transmitter. The outputs of the six high frequency accelerometers were not filtered in runs 1 to 15 of Sled No. 1; however, in runs 1 to 3 of Sled No. 2, 12-db-per-octave low-pass filters were interposed between the preamplifiers and oscillators of the high frequency vibration channels. Three-thousand-cps filters were used in the 40 and 22 kc channels and 2000-cps filters in the 70 kc channels.

The rf multiplex signals were received at the NOTS ground station with Nems-Clark 167-E receivers and discriminated with EMR 27c discriminators and standard EMR low-pass filters for recording on half-inch magnetic tapes via an Ampex 307/4 tape recorder with 500-type head spacing. Two of the four tracks on the half-inch tape contained vibration data from each telemeter link, while the third track contained Base coded time and the fourth track was used for voice annotation.

Each telemeter link was calibrated before and after each run by means of a five-step calibration interposed at the input to each subcarrier oscillator. This procedure provided a means for calibrating the telemetry-transmitter-receiver-ground station system. All accelerometers were initially calibrated on an electromagnetic shaker in the laboratory.

Calibration checks were employed twice during the course of the program by performing a straight-through shaker calibration. In this procedure, applied to the high frequency vibration links only, accelerometers were removed from the sled and mounted on a shaker near the telemetry transmitter. The accelerometers were connected to their preamplifiers and telemeters so that the signals generated by known sinusoidal accelerations could be telemetered to the NOTS receiving station in the same manner as sled vibration data. The shaker signals and the usual five-step telemeter calibrations were also transmitted and tape-recorded. One straight-through check was performed with Sled No. 1 and another with Sled No. 2. In both cases it was found that the two methods agreed to within 15 per cent.

Background noise levels were checked from time to time by leaving an accelerometer disconnected during a test run. Noise levels measured in this way appeared to be low relative to vibration signals.

Data Reduction

Multichanneled oscillograms were prepared from the half-inch standard magnetic tapes for each sled test run. Examination of the oscillograms after each run revealed the quality of the data as received from the telemetry instrumentation and aided in planning the next test run. Additional study of the oscillograms provided comparative information on acceleration environment for evaluation of sled performance.

Laboratory analysis of the data was started by using a Kay Electric Vibralizer to prepare spectral charts showing frequency analyses of the six high frequency complex vibration accelerations for the 15 to 1500 cps Vibralizer range. This type of chart (in which amplitude is indicated by intensity

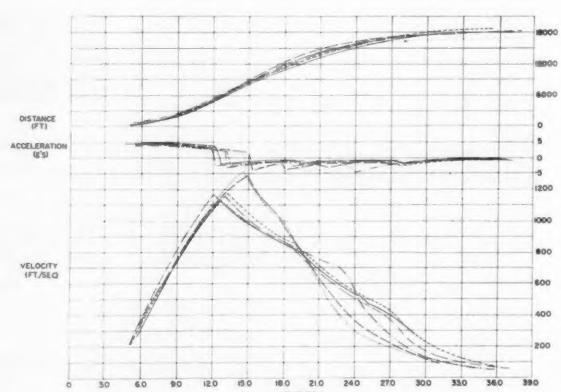

Fig. 2 Trajectory data from shake-down runs

Code

Sled 1, run 7	——- - ——- -	Sled 1, run 12	—— —— ——
Sled 1, run 9	——————	Sled 1, run 13	——· · · ——· · ·
Sled 1, run 10	- - - - - - - -	Sled 2, run 3	. . . .

Run Statistics

Run number	7	9	10	12	13	3
Weight of nose section, lb	1330	1566	1400	1620	1445	1800
Total weight of vehicle, lb	6900	7933	8037	8175	7990	7760
Duration of powered run, sec	8.5	8.5	9.3	11.4	9.3	10.6
Time of entry into water brake, sec	17.0	19.1	19.1	17.7	22.4	18.0

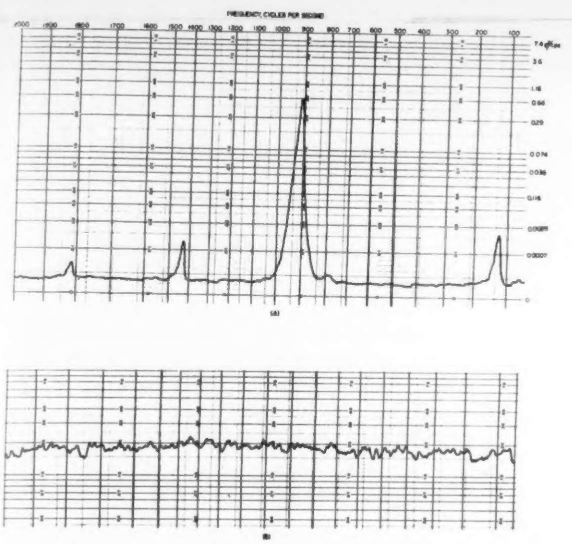

Fig. 3 Davies analyzer calibration records for high frequency analyses. (a) Sinusoidal signal from telemetered and tape recorded 6 g (peak) shaker calibration. (b) Random noise from a calibration tape

modulation in plots of frequency vs. time) was prepared for entire test runs. The charts were used to provide a semi-quantitative indication of the spectral distribution of the vibration, particularly with regard to the extent of variations from position to position within the nose and from run to run, and to provide a spectral "map" for selection of times for power spectral density analyses and for location of resonance frequencies and time intervals.

Power spectral density graphs were made using a Davies Automatic Wave Analyzer (with smoothing filter added) for 2-sec intervals at points within the test run where relatively stationary processes occurred. Calibrations on these charts are indicated as gravities squared per cycle per second (power spectral density). Two frequency ranges were used, 7 to 100 and 50 to 2000 cps. The Davies and Vibralizer analyzers are both sweep-frequency devices.

A Davies analysis of a 900 cps sinusoidal vibration signal is shown in Fig. 3(a). (The low amplitude side frequencies evidently represent spurious excitation.) Davies settings for this analysis (as well as for the other broad-band analyses presented in this paper) included a bandwidth of 6 cps, a tape circulation period of 2 sec, and an averaging sweep rate of 3 cps. The time constant of the smoothing filter added at the output was 2 sec. Fig. 3(a) indicates that the effective (dynamic) bandwidth was about 20 cps; the increase over the 6 cps bandwidth setting was due to the effect of the smoothing filter. Since this is an averaging rather than an rms effect, the amplitude of the sine wave analysis does not appear as large as it should. However, this distortion should not be important unless power spectral density is peaked in narrow frequency bands. The data for the most part do not show such peaks, and therefore the analyses are probably not particularly distorted. Evidence that the Davies analyses do show power spectral densities was provided by comparing the area under a power spectral density curve with the equivalent rms voltage measured at the output of the discriminator; the two determinations were in approximate agreement.

Fig. 3(b) shows the Davies Analyzer response to the white noise generated by a General Radio noise generator, and may be used together with Fig. 3(a) as a reference in interpreting the broad band Davies analyses.

A comparable narrow band analysis for the low frequency end of the spectrum is shown in Fig. 4. Davies settings for this analysis (as well as for the other narrow band analyses) included a bandwidth of 1 cps, a tape circulation period of 2 sec and an average sweep rate of 0.06 cps per sec. Because of this low sweep rate the effective bandwidth was also about 1 cps. In Fig. 4 the 60-cps peak was due to pickup in the calibration tape and the roll-off below 30 cps was due to the characteristics of the General Radio noise generator.

Errors

Average probable instrumental errors associated with the calibrations indicated in the Davies analyses are estimated in Table 1. These errors include accelerometer, telemeter, tape recording and Davies errors. The larger of the two figures given is applicable in each case.

Table 1 Average probable instrumental errors (Davies)

Amplitude	Sled No. 1	Sled No. 2
Broad band analyses	20% or 0.0003 g^2/cps	20% or 0.01 g^2/cps
Narrow band analyses	30% or 0.003 g^2/cps	30% or 0.01 g^2/cps
Frequency	0.5% or 0.2 cps	0.5% or 0.2 cps

In addition to the calibration errors in Table 1, distortion errors of the Davies were present. As stated, the distortion is associated with lack of square law detection and is important if power spectral density changes abruptly. Its effect may be inferred from Figs. 3 and 4.

Statistical variations associated with the limited duration of the random vibration samples analyzed should also be considered in interpreting the results. Such variations will have the effect of random error on generalizations based on the analyses. The effect of the variations may be seen in the white noise analyses of Figs. 3 and 4.

Spectral Vibration Analysis

The vibration data were obtained at relatively solid reference points in the nose structures. In Sled No. 1, which is illustrated in Fig. 1, these points were at (a) the base of one of the rear uprights supporting a dummy gyro component at

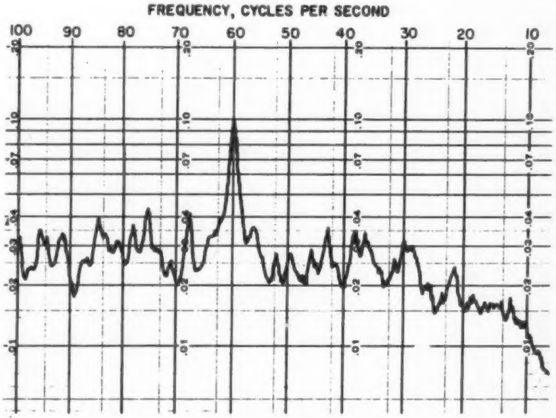

Fig. 4 Davies analyzer calibration records for low frequency analyses; random noise shown is from same tape as Fig. 3

Table 2 Vibration data for Sleds No. 1 and 2

Sled No. 1 Location	Direction	Run	Total rms acceleration, g	Peak power spectral densities, g^2/cps	Range of peak, cps
Average velocity					
480 to 1060 fps (accelerating)					
Base of gyro component support member	vertical	9	4	0.03	20–200
		10	4	0.1	30–200
		10[1]	4	0.1	30–80
				0.03	80–200
	axial	13	6	0.1	150–250
	transverse	9	8	0.1	7–15
				0.1	150–250
VMS support member	vertical	7	6	0.1	10–25
				0.1	50–100
				0.1	700–800
	axial	7	4	0.03	100–150
	transverse	7	7	0.03	10–20
				0.1	600–800
1130 fps (peaking)					
Base of gyro component support member	vertical	10	10	0.3	100–200
				0.03	800–1500
Sled No. 2					
1060 fps (decelerating)					
Electronics package support member	vertical	3		1	80–120
	axial	3		0.3	60–120
				0.1	1000–1300
	transverse	3	15	0.3	7–12
				0.1	100–150
				0.1	1000–1700
Top of central ring	vertical	3		1	80–150
				1	1500–1800
	axial	3		0.1	40–450
				0.1	600–900
				0.1	1500–1750
	transverse	3	28	0.1	7–15
				1	150–200
				1	1500–1750

[1] Data for deceleration.

the rear of the nose section and (b) the front end of the longitudinal member supporting the velocity measuring system telepack. In Sled No. 2 the points were at (a) the top of the central ring structure and (b) the sled frame end of one of the members supporting a dummy electronics package. The latter two locations are illustrated in Fig. 5 at points R and Q respectively. The mounting arrangement of each group of three accelerometers on its block may also be seen in the photograph.

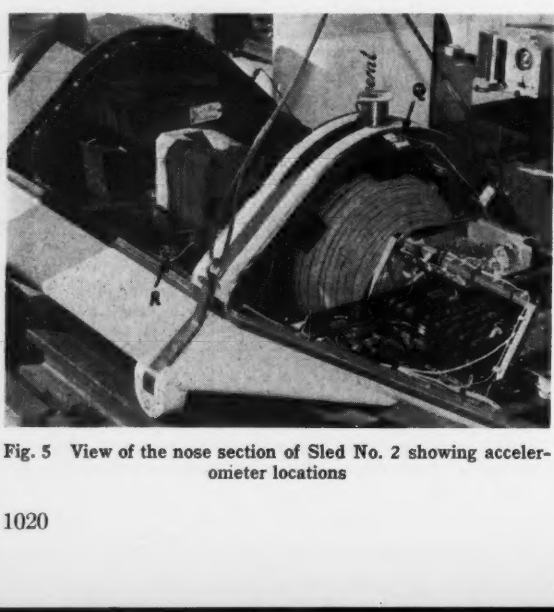

Fig. 5 View of the nose section of Sled No. 2 showing accelerometer locations

The data are believed to be spectrally significant to frequencies of about 1000 cps. From 1000 to 2000 cps, spectral details are probably influenced by minor resonances of each block with its group of three accelerometers and by dynamic reactions of each block on adjacent structures.[2]

Conclusions

The following conclusions have been drawn from the data obtained:

1 Nose section vibration was generally random in nature and evidently due to excitation of numerous structural modes caused by track constraints and aerodynamic effects. The engine contributed relatively little vibration directly, at least for medium and high sled velocities. Water braking did not seem to be an important contributor to vibration. Thus, the vibration for a particular sled configuration was determined primarily by sled velocity. An exception to the random vibration was occasional sinusoidal vibration near 270 cps caused by the track "sleepers."

2 There was no particular starting shock, but rather a burst of oscillations which soon died down and (at high sled speed) was exceeded in amplitude by the intense continuous vibration which built up as sled speed increased.

3 Spectral features were usually quite consistent throughout a run.

[2] A number of spectral analyses of sled data were presented at the ARS Spring Meeting. These analyses may be obtained from the authors.

4 Spectral characteristics and intensity levels were rather closely reproduced from one sled run to the next.

5 Sled No. 2 appeared to have vibration acceleration levels approximately twice those of Sled No. 1.

6 There was only limited correlation between vibration characteristics measured in the three coordinate directions at a point.

7 Vibration tended to be more intense in the vertical and transverse directions than in the axial direction; however, there were no consistent differences between the axes.

8 There was little spectral correspondence between vibration characteristics measured at points several feet apart except at frequencies below about 40 cps. On the other hand, there were no very marked differences in general vibration intensity from position to position within a sled.

9 The tabulation (Table 2) of order-of-magnitude power spectral density levels may be regarded as representative of peak levels encountered for 2-sec. intervals during the shake-down sled runs. Corresponding values for total rms acceleration over the frequency range 7–2000 cps are included.

Precision Measurement of Supersonic Rocket Sled Velocity —Part I—

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Preface

THE use of a supersonic rocket sled for testing components of all-inertial guidance systems is very attractive, but it implies a very precise measurement of sled velocity over a relatively wide frequency bandwidth. Typical figures are 0.1 fps velocity error and 100 cps bandwidth.

Most sled tracks have a system of position markers furnishing time as a function of position during a run. This discrete data can be differenced to obtain approximate velocity, but with any practical combination of marker accuracy and spacing the desired velocity accuracy and bandwidth combination cannot be obtained, due to the emphasis of high-frequency noise by the differentiation process and the fold-over or aliasing of higher frequencies.

On the other hand, the higher frequency components of velocity are easily obtained to the desired accuracy by integration of the output of a sled-borne accelerometer of moderate accuracy. Of course, the accuracy of the low-frequency components so obtained will be very poor. The desired velocity accuracy and bandwidth combination can be obtained by suitably combining the data from such an accelerometer with relatively infrequent track time and position data of practical accuracy.

A method of combining track-coil and accelerometer data is proposed. The method combines computational simplicity with the required precision. A detailed error analysis of the method is presented in Part II of this paper (to be published in a forthcoming issue of JET PROPULSION).

Introduction

The supersonic rocket sled is unique in its ability to provide large linear accelerations of relatively long duration with dependable recovery of test equipment in undamaged condition. The use of such a sled for testing components of inertial guidance systems is very attractive for several reasons, but it implies a very precise measurement of sled velocity over a relatively wide frequency bandwidth, that is, the velocity must be accurately determined even during rapid changes.

1 Velocity Measurement

A test proposed for one inertial guidance system involves a maximum velocity in the neighborhood of 2000 fps. For the purposes of this test, it is desired that the track instrumentation system be capable of measuring the velocity of the sled along the track to an accuracy of 0.1 fps or better.

If we assume the velocity is being passed through a low-pass filter consisting of a second-order servo with error rate damping of 0.7 critical and natural frequency ω_n, then the maximum transient error in velocity due to a discontinuous change in acceleration (velocity slope) of $\Delta\alpha$ is

$$0.23 \frac{\Delta\alpha}{\omega_n} \text{ fps}$$

If we take 0.1 fps for the maximum velocity error and $\Delta\alpha = 250$ fps^2, the required natural frequency of the filter is 92 cps.

At first sight it might appear that the above combined accuracy and bandwidth requirement would be very difficult to satisfy and that the possibility of getting along with a reduced requirement at the expense of more complex test procedures should be considered. However, it is shown below that the requirement is, in fact, not difficult to satisfy and so there is no strong reason to consider reducing the requirement. Had it been impractical to satisfy the requirement, then velocity information over a reduced bandwidth could be obtained by subtracting the track instrumentation velocity from the guidance velocimeter output and passing the difference through a low-pass filter of sufficiently low cutoff frequency.

Presented at the ARS Spring Meeting, Washington, D. C., April 4–6, 1957.

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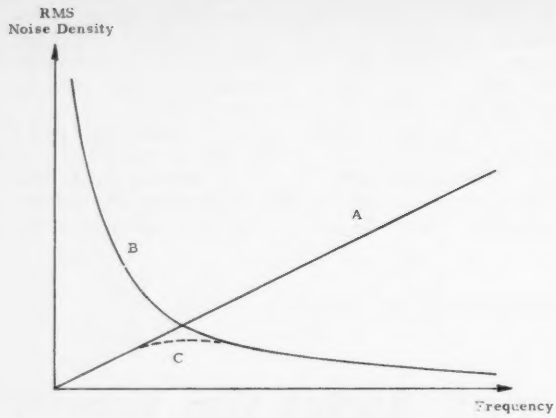

Fig. 1 RMS spectral density of velocity noise for (A) differentiated position, (B) integrated acceleration and (C) optimum combination of the two

2 Use of Combined Position and Acceleration Data

It is not practical to measure sled velocity directly. Instead it can be obtained by differentiating the position vs time record or by integrating the acceleration (force) vs. time record. Time, position and force are all easy to measure directly, in contrast with the difficulty of measuring velocity directly (such as by the use of viscous or magnetic devices).

Although velocity can be obtained from either position or acceleration data, the situation with respect to errors is quite different in the two cases. Any measurement system will have random errors associated with it equivalent to noise in a communication system. In most position measurement systems, including track coil and similar sled position schemes, the noise has a fairly constant spectral density up to some limiting frequency. Thus, when the position information is differentiated to obtain velocity, the rms noise spectrum is multiplied by the angular frequency (emphasized at 6 db per octave) so that the velocity noise spectrum appears as curve A in Fig. 1. On the other hand, in acceleration measurement systems the noise spectral density is likewise fairly constant up to some limiting frequency with perhaps some rise at very low frequencies. Thus when the acceleration information is integrated to obtain velocity, the rms noise spectrum is divided by the angular frequency (de-emphasized at 6 db per octave) so that the velocity noise spectrum appears as curve B in Fig. 1. Clearly the best results are obtained by using differentiated position data for the low frequency components of velocity and integrated acceleration data for the high frequency components of velocity. More precisely, the two data are combined by a frequency-dependent weighted mean to give the noise spectral density indicated by curve C of Fig. 1. This will be treated in greater detail in Section 4 and in Part II of this paper.[3]

3 Differentiation of Discrete Position Data

The position vs. time data obtained from a track-coil or similar system is discrete with equal increments of position. However, it will become apparent that it is valid to carry out the analysis on the basis of assumed equal increments of time provided these are not less than the largest of the actual increments of time. In other words, the analysis is valid for sled velocities greater than the critical value corresponding to the assumed equal increments of time.

Let $x(t)$ be the sled position as a function of time and let h be the equal increments of time. Then the actual discrete data available are

$$x_n = x(nh), \qquad n = 0, 1, 2 \ldots \ldots \ldots \ldots [1]$$

It is not possible to compute an exact derivative from these discrete data, but a simple approximation for the velocity is

$$v_n = \frac{x_n - x_{n-1}}{h} \ldots \ldots \ldots \ldots [2]$$

where the subscript n on v indicates that the discrete velocity approximation is the average value over the interval from x_{n-1} to x_n. If the actual velocity is changing linearly with time, then v_n is the actual value at the center of the interval. In other words, a time delay of $h/2$ is introduced by the approximate velocity calculation. We shall not view a time delay as an actual error since it is easily taken into account when the data are analyzed after the test. In case the velocity is not changing linearly with time, there will be an error in velocity magnitude in addition to that caused by the time delay. In terms of the frequency domain, it is instructive to analyze this error in two parts. The first part is due to the simple filtering action of the discrete differentiation approximation defined by Equation [2]. The second part of the error is due to the foldover or aliasing of the higher frequency components to lower frequencies by the sampling process.

We can better understand the first part of the discrete differentiation error by introducing the concept of the equivalent continuous filter for the simple example of the discrete differentiating filter defined by [2]. The equivalent continuous filter is defined by

$$v(t) = \frac{x(t) - x(t-h)}{h} \ldots \ldots \ldots \ldots [3]$$

This operates on the continuous function of time $x(t)$ to give the continuous function $v(t)$. Now the discrete velocity approximation v_n can be obtained from $v(t)$ by

$$v_n = v(nh), \qquad n = 0, 1, 2 \ldots \ldots \ldots \ldots [4]$$

Thus the error in [2] can be obtained by first calculating the transfer function of [3] followed by an application of the sampling process defined by [4].

The transfer function $G(\omega)$ of the equivalent continuous filter described by [3] is given by

$$G(\omega) = \frac{1 - e^{-ih\omega}}{h} = \frac{\sin (h\omega/2)}{h/2}\, e^{i(\pi/2 - h\omega/2)} \ldots \ldots [5]$$

where $i^2 = -1$. Now the transfer function for an ideal differentiator is $\omega e^{i\pi/2}$, so it is clear from [5] that, aside from the time delay $h/2$, the magnitude of the error transfer function $G_e(\omega)$ of the approximation differentiation is

$$\left| G_e(\omega) \right| = \left| \frac{\sin (h\omega/2)}{h/2} - \omega \right| \ldots \ldots \ldots \ldots [6]$$

[3] "Precision Measurement of Supersonic Rocket Sled Velocity—Part II" is to be published in a forthcoming issue of JET PROPULSION. This paper will be referred to as Part II.

Now the power spectrum of the error due to the approximate differentiation by the equivalent continuous filter is just the product of $|G_\epsilon(\omega)|^2$ with the power spectrum $\psi_x(\omega)$ of the position signal $x(t)$, and the total mean square value of this error is given by

$$\overline{(\epsilon^2)}_{f_i} = \int_0^{\omega_c} \left| G_\epsilon(\omega) \right|^2 \psi_x(\omega)\, d\omega \qquad [7]$$

where ω_c is the highest frequency in $\psi_x(\omega)$.

If we now return to the discrete data by sampling the filter output in accordance with [4], the mean square value of the error in the samples will be the same as that in the continuous filter output provided there is no correlation between the sampling process and the continuous signal—and there is none.

In our special example for $G(\omega)$ given by [5], there are no parameters to be optimized for minimum error once the sampling time increment h is given. However, in the general case where the velocity is computed from $n + 1$ equally spaced samples of position, the transfer function equivalent to [5] becomes

$$G(\omega) = \sum_{l=0}^{n} W_l e^{-ilh\omega} \qquad [8]$$

where the weighting parameters W_l may be varied to minimize [7]. If $\omega_c < h/\pi$, then the differentiation error [7] can be made arbitrarily small by taking n sufficiently large. However, if $\psi_x(\omega)$ contains components with frequencies equal to or greater than half the sampling rate $1/h$, part of these will be passed by the equivalent continuous filter and then sampled. The sampling of these higher frequencies immediately introduces the foldover or aliasing effect whereby the samples from a higher frequency component $\omega \geq \pi/h$ are identical with the samples that would have come from a lower frequency component $\omega_a < \pi/h$ given by

$$\omega_a = \min_m \left| \omega - m\pi/h \right| \qquad [9]$$

where m runs over the positive integers.

From the frequency domain point of view, this ambiguity can only be viewed as an error in the low frequency components of the discretely differentiated data. This frequency ambiguity, of course, exists in the discrete position data before any attempt at differentiation. Although this foldover or aliasing error has a mean square value $\overline{[\epsilon^2]}_{af}$ which can be calculated(1)[4] from $\psi_x(\omega)$ and $G(\omega)$, we shall not pursue this because, in accordance with Part II, *it is possible to use the high frequency components from the integrated accelerometer data to eliminate the foldover or aliasing error in the track-coil data.*

Leaving aside the foldover or aliasing effect, the error [7] is not the total error but only that part of the error due to the distortion of the noise-free signal by the approximate differentiation. The remaining part of the error is due to the noise[5] passed by the differentiating filter. If the spectrum of the noise is $\psi_n(\omega)$, then the mean square error due to the noise is

$$\overline{(\epsilon^2)}_n = \int_0^{\omega_c} |G(\omega)|^2 \psi_n(\omega)\, d\omega \qquad [10]$$

[4] Numbers in parentheses indicate References at end of paper.

[5] The term "noise" as used herein refers to errors in position measurements (resulting from inexact location of the track markers and flexure of the sled magnet support) and errors in time-interval measurements. In the analysis these are identical with noise as defined in communication theory.

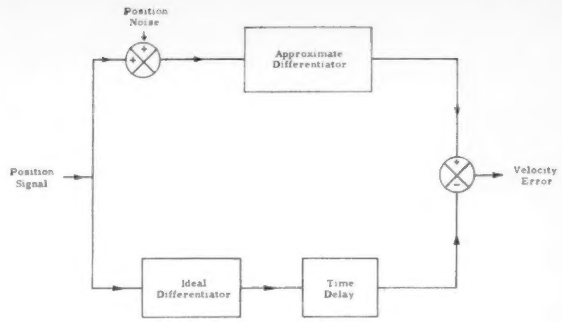

Fig. 2 Block diagram of error computational process

The approximate differentiation filter will be optimized when $G(\omega)$ (and therefore $G_\epsilon(\omega)$) is adjusted to minimize the sum of Equations [7 and 10]. Of course, in adjusting $G(\omega)$ there will be certain constraints to be satisfied such as the value of the increment h and the number n of signal sample pairs available. With h and ω_c fixed, it is found that, as the number of samples (length of memory) available to the optimum discrete filter is increased, the error at first decreases rapidly and then approaches a limiting value. As the number of samples becomes large, the performance of the filter approaches that of the optimum Wiener infinite memory filter. A block diagram of the error computational process just described is given in Fig. 2. The time delay following the ideal differentiator is to remove the error due to the time delay in the approximate differentiator.

In Part II the differentiation of track position data is analyzed along the lines of the theory just discussed, and it it shown that, even with optimum velocity filtering and neglecting the foldover or aliasing error, no practical combination of track-position-marker parameters will come close to satisfying the velocity requirement of 0.1-fps maximum error and 100-cps bandwidth.

A little thought will show that operation of a continuous-wave Doppler radar system is equivalent to establishing an equally spaced set of track-position markers. The spacing is half a wave length at the radio frequency used (distance between zeros of the interference between local and reflected signals). The accuracy of marker location is determined by a number of things, including accuracy of radio frequency, signal-to-noise ratio, ground reflection, etc. In the usual Doppler radar there must be a differentiation of position (phase of Doppler signal) to obtain velocity (frequency of Doppler signal). This differentiation actually involves the same considerations just discussed for a physical track-marker system.

It is possible that the closer marker spacing, and possibly improved position accuracy provided by the Doppler radar would permit our velocity requirement to be satisfied. However as pointed out in the next section, the combination of position data from a practical system of physical track-position markers with sled acceleration data will also satisfy our velocity requirement.

4 Optimum Combination of Position and Acceleration Data

Let us now return to the situation described by Fig. 1 in which we wish to obtain a frequency-dependent weighted mean of the velocities obtained from differentiation of position and integration of acceleration. This must be done by

the two filters Y_1 and Y_2 as shown in the block diagram of Fig. 3. Using the optimization concept previously discussed, the two filters are chosen with amplitude vs. frequency characteristics to minimize the sum of the mean square errors resulting from distortion of the signal by the filters and noise passed by the filters. It is not possible to realize filters with such amplitude vs. frequency characteristics unless accompanied by certain time-delay characteristics; that is, in order to compute the present data output the filter must have future data input. In the measurement of sled velocity this is easily carried out, since the data for an entire run is available before the velocity filtering computation starts.

In the sled velocity measurement problem the noise is very small relative to the signal. In this case a very close-to-optimum result is obtained by requiring that the error due to distortion of the signal by the filters be zero and then adjusting for minimum noise error.[6] This procedure is carried out in Part II where a composite velocity error is obtained based on assumed position and acceleration errors. This result forms a greatest lower bound for any method of combining the track and accelerometer velocity data. The result shows that the requirement of the first section can be met with available track-position systems and accelerometers.

5 A Simple Computational Procedure for Obtaining Velocity from Position and Acceleration Data

The computational procedures equivalent to a truly optimum filter system, as analyzed in Part II, may be quite extensive while those required for a close-to-optimum system may be very simple. In addition, Part II describes and analyzes in detail a close-to-optimum system which because of its simple computational requirements should be most practical for reducing sled-test position and acceleration data to velocity.

[6] Under this condition the data combination can be accomplished with the single filter Y_1, as shown in Fig. 4.

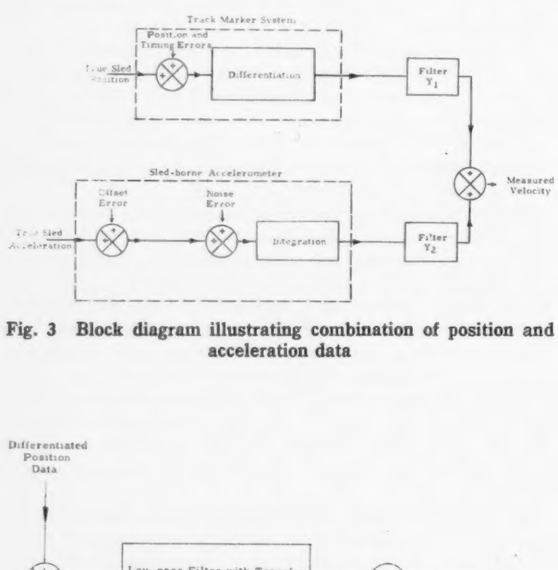

Fig. 3 Block diagram illustrating combination of position and acceleration data

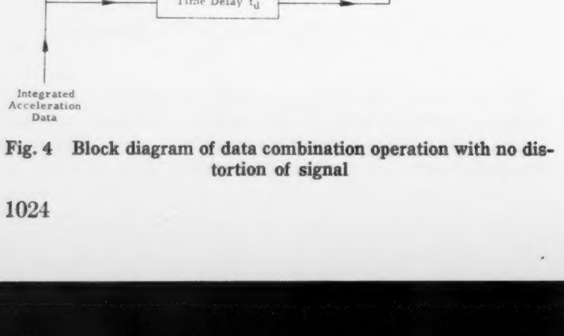

Fig. 4 Block diagram of data combination operation with no distortion of signal

The system is carried out in two steps. In the first the doubly integrated accelerometer data are compared with track-position data at three points to obtain corrections for the average zero-set and scale-factor errors of the accelerometer during the track run. The corrected accelerometer data are then integrated once to obtain a "first corrected" velocity. In the second step the average value of this first-corrected velocity from the accelerometer is compared with the average velocity determined by the differenced track time-position data over suitable intervals. This is used to obtain step corrections which are added to the first-corrected velocity to provide a "second corrected" velocity.

The analysis shows that, under reasonable assumptions and conditions, the second corrected velocity meets the requirement of Section 2. A comparison of this system with the optimum method of Part II shows that the system is indeed close to optimum.

6 Location of Measurements on Sled

Since the sled is not rigidly coupled to the track, it is expected that there can be appreciable velocity differences (relative to 0.1 fps) between various parts of the sled and also across vibration isolation mounts on which the inertial equipment may be installed. Of course, the point where the velocity measurement is desired is at the mounting of the inertial equipment under test. Very likely the sled-borne instrumentation accelerometer can be mounted at this point, but sled position would normally be measured at some other location. In this case it would be necessary to measure the relative displacement between the desired point of velocity measurement and the location where the sled position measurement is made.

7 Velocity Measurement System Analysis and Simulation

The analysis and simulation program which has yielded the results described above constitutes Part II of this paper, and will appear in a forthcoming issue of JET PROPULSION.

The analysis of Part II may be conveniently divided into three sections:

1 It is demonstrated that any practical system of providing discrete position data is inadequate for determining the velocity with sufficient accuracy and bandwidth.

2 Optimum methods of combining acceleration and position data are studied. A lower bound is established on the velocity error under assumptions of stationarity.

3 The procedure for combining acceleration and position data described in Section 5 is analyzed in detail. The equations to be mechanized are presented, and a complete error analysis is performed.

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2 Naval Ordnance Test Station Staff, "A Precision Velocity-Measurement System for SNORT," NAVORD Report 5247, April 1956. (This is a general reference on the velocity measurement system to be installed at the SNORT track.)

Sled Testing the Emergency Escape System: The Human Factor

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Introduction

ANY sled test program for development and qualification of an aircraft escape system should encompass thorough evaluation of objective, test facility, test vehicle, instrumentation, test subjects and data.

Objective

NAA's current escape system test program was planned and approved by the Air Force over a year before the first test run. The over-all objective in this program was to develop and prove an escape system for a high speed aircraft. One objective was to test the individual elements of the system—canopies, seats, catapults, helmets, lap belts, flying suits and oxygen equipment—under the effects of ejection. All these items had to function properly under conditions which simulate the flight envelope of the airplane. Previous research had indicated that in order to attenuate the damaging effects of thrusting an escape unit into a high speed, high density airstream, the orientation of the escape unit must be controlled. Our principal objective was to demonstrate that the escape unit would provide protection to the crew member for escape from the airplane without injury, or with minimum injury at all speeds within the flight envelope of the airplane. This meant that all elements of the system must be tested together, and under the environmental conditions of the airplane. For instance, the ejection of the canopy must not cause injury to the crew member or even create a hazardous situation which might jeopardize the reliability of the remainder of the escape system. The pilot, or crew member, must retain his helmet, visor, clothing, survival gear, and oxygen system for protection and use during escape. Further, our primary objective must be accomplished within the time limitation set for qualification of the airplane. It would be desirable to qualify the escape system by the time the airplane prototype flight tests are completed, but this must be done before delivery of the first airplane to the customer. There were secondary objectives, such as correlation of test results with other data, developing test techniques for securing and recording the data, measuring the forces, accelerations, windblast pressures, velocities, trajectories and sound levels.

Test Facility

Most of our tests were performed at the Edwards AFB high speed track, which we found quite adequate for the accomplishment of our objectives.

Test Vehicle

Our test vehicle (Fig. 1) was designed for 16 standard 2.2 ks solid propellant rocket motors. Each motor has a thrust of 11,000 lb for 2.2 sec. The maximum sled weight including the 16 motor units was around 8000 lb at blast-off. The forward end of the test sled was identical to the airplane in contour. The canopy, cockpit, consoles, windscreen, seat and all escape mechanisms were duplicated in the sled. Canopy and seat ejection were initiated as the sled passed over screen boxes placed at predetermined positions along the rails. The screen boxes delivered electrical power to the cutter knives mounted beneath the sled. The electrical current picked up by the cutter knives fired squib activated thrusters which pulled the firing pins on canopy and seat catapult initiators. Standard AF initiators and catapults identical to the airplane system were used throughout.

Instrumentation

The importance of reliable instrumentation can never be overemphasized—one good record is worth a thousand guesses. This applies to oscillograph as well as photographic records. In some of our tests, we used 24 channels of telemetering supplied by three transmitters in the sled and one transmitter in the dummy. In addition, there were 38 high speed motion picture cameras, including five on the sled, used in each test. Even with all this carefully planned instrumentation, we never felt that we had too much information.

The telemetering channels were used for recording three axis acceleration in the head and torso of the dummy, dynamic windblast pressure in the dummy head, and 15 strain gage channels on the seat and canopy, plus sound pickup in the cockpit.

Presented at the ARS Spring Meeting, Washington, D. C. April 4–6, 1957.

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[2] Senior Engineer, Human Factor Group.

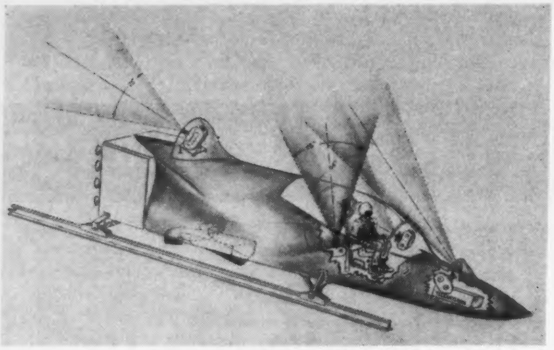


Fig. 1 Test vehicle

Fig. 2 Guided catapult stroke—Trajectory comparison, M-3 catapult, 200 Knots

Camera instrumentation consisted of 16 mm high speed motion picture cameras and Hulcher cameras. Sled cameras were mounted as shown in Fig. 1, and placed so as to observe the operation of the escape system from just before the ejection until after the seat-dummy unit would have passed over the tail of the airplane. Sled-borne cameras were closest to the action, and had the least relative motion to the escape unit during ejection. After each test the film was flown to Los Angeles, developed, and viewed by project engineers and human factors specialists within 3 hours. This enabled designers and escape system specialists to evaluate the results of each test immediately, so that any indicated changes could be incorporated in the system before the next test. Hand-panned 70 mm Hulcher cameras with long focal length lenses were stationed 500 to 800 ft from the track opposite the trajectory area, to cover the ejection trajectories of both the canopy and the seat and dummy. Hulcher film was also quickly processed and enlarged prints were available for detail analysis in the evening following the test. In addition to the sled cameras and the Hulcher cameras, there were 19 metric range cameras, 6 trackside cameras, and 8 hand-panned cameras, all 16 mm motion picture cameras, operated by Edwards AFB Photograph Branch.

Results

The more than twenty ejection seat sled tests conducted by NAA during the past 17 months produced a number of interesting results:

Seat Stabilization or Orientation. In our efforts to obtain the proper orientation of the seat-dummy unit as it was thrust into the airstream, a number of stabilization methods which looked promising in wind tunnel tests were tried and compared in a sled test series. Our object was to orient the seat with the vertical axis approximately 65 deg aft of vertical, which placed the seat in the lowest drag but maximum lift attitude, while it placed the crew member in the seat in a most favorable attitude for tolerating deceleration forces. In addition, the seat bottom provided protection for the occupant and personal equipment from direct windblast.

In the first tests we employed a 29-in. conical FIST ribbon-type parachute attached to the back of the seat with long riser lines. The parachute was deployed by means of a gas operated catapult as the seat was ejected. It soon became apparent that stabilization of an escape unit at supersonic speed involved a lot more than merely attaching a ribbon chute to a seat. There were parachute deployment problems, mechanical difficulties, and unforeseen secondary instability characteristics to be worked out. The single chute with the long riser lines did not seem to be the answer. Even if we could take care of the deployment, mechanical and secondary instability problems, at best this system would provide stability along one axis only, and there was always the possibility of the long risers becoming entangled with the seat and man, particularly at low airspeed. Even though the tests showed that the single parachute did stabilize the seat in pitch, there was much yawing and rolling, and at low airspeeds the risers wrapped around the man.

Therefore, we decided to try twin stabilizer chutes, of a much smaller ribbon type (10 in.), attached to the ends of arms deployed on each side of the seat near the top. There were several advantages to the twin chutes: They provided stability along two axes, there were no risers to entangle the seat occupant, deployment was simple since the chutes were stored in the arms, positioning of the arms during the ejection took care of deployment simultaneously. Although wind tunnel tests of this configuration indicated that 14-in. parachute support arms were long enough, we found that the parachutes became blanketed by the seat at high speed. Further sled tests proved that the support arms had to be extended to a length of 26 in., making the two support points for the parachutes 72 in. apart. We also discovered that the parachutes had to be reefed at the skirt to prevent "squidding" at high speed. Thus we were able to arrive at the design parameters for a seat stabilizer system which will orient the seat-man unit effectively at both high and low airspeeds.

Guided Catapult Stroke (Fig. 2). In upward ejection escape systems, the problem of tail clearance, of course, becomes more critical as the speeds increase. The higher velocities cause higher drag loads and increased negative lift on the seat. The higher drag loads cause greater seat rail friction, which, combined with the negative lift, decreases the ability of the catapult to produce the desired upward velocity. Thus, as the speed at ejection goes up, the velocity of the seat-man unit toward the tail increases, while the upward velocity decreases. Earlier studies indicated that to solve the problem of tail clearance at high speed, without either getting rid of the tail or finding a more powerful catapult, two things could be done: The rail friction could be reduced to a minimum and the catapult stroke could be fully guided. Telescoping rails and frictionless bearings in the seat rollers were incorporated in the system. These design concepts proved to be sound when tested. In subsequent ejections at much higher speeds we were able to obtain adequate tail clearances.

Helmet and Oxygen Mask Retention. Another inherent problem of escape is the retention of helmet and oxygen mask. Before final evaluation, new helmet and mask retainer designs were tested on a boom attached to a high speed sled in such a manner that the effects of the wind-blast could be observed by high speed cameras mounted inside the sled. After it was determined that the helmets and mask retention systems could withstand the free airstream at various angles of at-

Fig. 3 Helmet and oxygen mask retention

tack, without either sustaining major damage or coming off the boom, several of the most promising designs were tested as part of the ejection seat tests by installing them on the dummy. It is noted here that the Protection Incorporated Toptex helmets with oxygen mask retainer and suspension system shown in Fig. 3 were successfully tested by ejection on dummies at airspeeds considerably in excess of 600 knots.

Personal Equipment and Survival Gear. In the course of our tests a number of interesting deficiencies were uncovered. In sonic speed ejections it was discovered that the automatic-opening lap belt manual lock unlatched as the seat left the cockpit. In another test we discovered that mechanically operated timing devices may be subject to unreliable operation under g loads. We were unsuccessful in trying to use an F-1A timer as a sequencing device on an ejection seat. This timer may be adequate for the purpose of opening parachutes, but the clock escapement mechanism operates in an unpredictable manner when used for other purposes. In this case the timer was used for firing the lap belt opener initiator. Apparently g forces caused the timer to operate before the release cable was pulled, resulting in premature firing of the lap belt initiator.

Free Airstream Testing of Helmets. The Toptex helmet was mounted on a test sled boom so as to expose it to the free airstream at airspeeds slightly over Mach 1.0. This technique enabled us to measure the actual load on the hose with a Brinnell tensiometer and thereby develop an oxygen hose retention system and prove out the ability of helmets and oxygen mask retainer systems to withstand airblasts during supersonic ejections.

Cockpit Pressurization. By pressurizing the sled with a portable low pressure pump, ground-stationed externally, and using a quick breakaway fitting, we could pressurize the cockpit right up to the instant of rocket firing, thus eliminating the necessity for providing pressure storage bottles and reduction valves on the sled. This method resulted in a saving of nearly 100 lb.

Stiffening of Dummy Joints. In all tests the dummy's joints were stiffened to a standard set of torque values chosen to represent maximum values of a human subject under similar conditions. This enabled us to correlate information on limb movement in various test runs at different airspeeds.

Three Axis Accelerometers in Head and Torso. Fig. 4 shows how the six accelerometers were installed in each ejected dummy. Fig. 5(a) presents an analysis of the data derived fromthe head-mounted accelerometers in tests of three different seat configurations. Configuration A was a seat with no con-

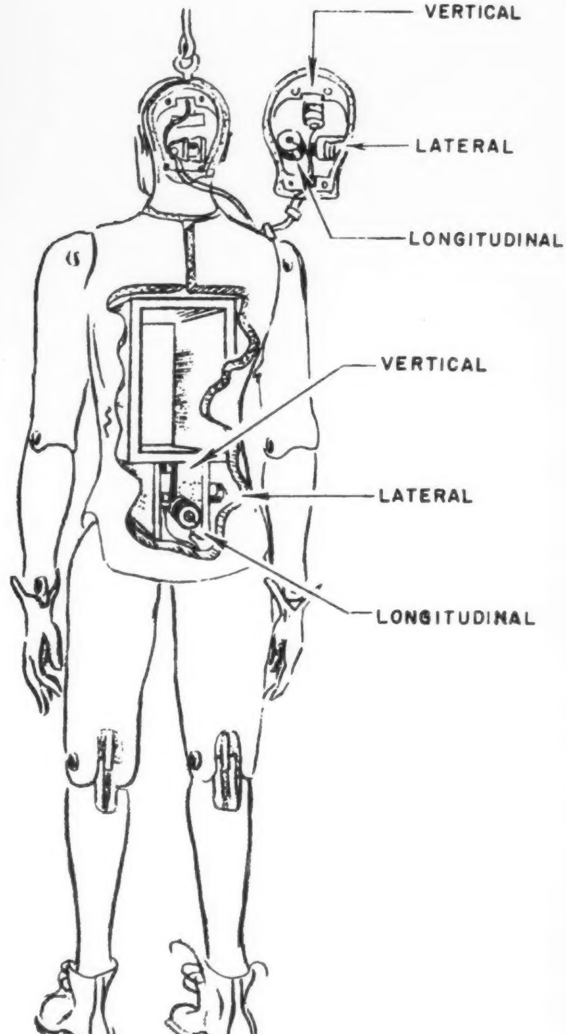
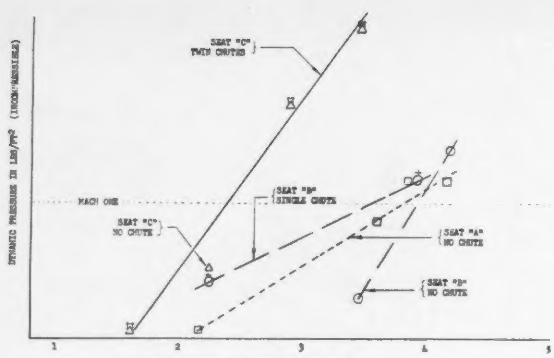


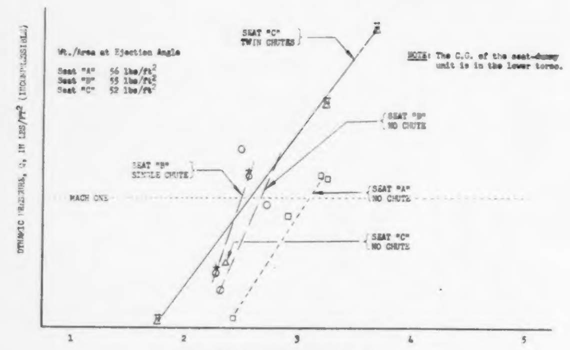
Fig. 4 Accelerometer installation

trol of aerodynamic pitching moment. Note the large relative accelerations. Configuration B, shown with and without parachute, was a seat with single stabilizer chute, and Seat C incorporated twin stabilization parachutes on a more nearly optimum structural shape, producing effective orientation so that the slope of the acceleration vs. dynamic pressure curve is much more favorable. One test point for Configuration C with no parachute is also shown. Fig. 5(b) demonstrates the absence of additional total drag which may have been expected by incorporation of the stabilizing parachutes. Accelerations at the center of gravity of the seat-man unit are actually lowered somewhat by proper orientation of the seat.

Recording Dynamic Pressure in Dummy Head. A probe was



(a) Maximum head



(b) Maximum lower torso

Fig. 5 Graphical analyses of acceleration data

connected to the Daytran absolute pressure transducer inside the dummy's head. The dynamic pressure variations experienced by the dummy head were transmitted by telemetering in the dummy during the sled run, when the canopy was ejected, and throughout the ejection trajectory, and were recorded on the oscillograph at the receiver station. A very close correlation was observed between the theoretical dynamic pressures encountered and the recorded pressures as the dummy was thrust into the airstream. It was also noted that the pressure readings varied directly with the head longitudinal accelerometer readings.

Recording Cockpit Noise. Cockpit noise is a very important physiological factor about which we have insufficient data in the realm of supersonic speeds. An Altec microphone was installed just above the cockpit console to measure sound levels throughout the range from 200 to 15,000 cycles. The results thus far have shown that the noise level is too high to get continuous records. For instance the microphone always goes off scale as soon as the canopy is ejected.

Fastair Cameras on Sled. Until the Fastair camera became available, the only high speed cameras which were rugged enough and reliable enough to operate under the high accelerations encountered were used for observing the ejection sequence, but they were large and heavy (20–34 lb). The new 70 "G" Fastair weighs 9 lb and is more rugged. Without sacrificing reliability, we now have four cameras for the weight cost of one.

Special Lightweight Battery. In powering our four sled cameras we were able to effect another big weight saving. The battery now used weighs 7 oz compared with 70 lb for a 28 volt lead-acid type.

Hulcher Camera Technique. Although the use of the Hulcher camera for sled work is not new, we discovered that at speeds above 1000 fps with the cameraman 450 ft from the track, the angular tracking velocity was reduced to a value well within the capability of the human operator. The image size was maintained by doubling the focal length of the lens to 20 in., and there was no apparent loss in definition.

Special Tracking Devices for Cameras. A double camera installation was found practical and proved to be invaluable more than once. We could operate one camera at a high and the other at a low frame rate, or one camera with long focal length and the other with short, one camera with black and white and the other with color. In the event of failure of one camera, we got the picture with the other. A special sight and stock enable the cameraman to track unimpeded at maximum angular velocity which now exceeds 120 deg per sec.

The Development of RESCU[1] Mark I

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FAST-PACED development of today's military aircraft permits the breaking of speed and altitude records with striking regularity. This continual increase in the flight performance envelope has aggravated the task of design engineers in providing an escape system for each new configuration. The problems associated with escape from these high performance aircraft may be categorized as: (a) Low level ejection, (b) fin clearance, (c) tumbling (seat instability) and (d) windblast.

Presented at the ARS Spring Meeting, Washington, D. C., April 4–6, 1957.

[1] Rocket ejection seat catapult, upward.

[2] Design Group Engineer, Interceptor Cockpits.

Low Level Ejection

Split seconds count when ejecting near the ground, and no time must be wasted in separating the occupant from the seat and deploying the personnel recovery parachute. Safe escape at or near the ground level fundamentally depends on the swiftness of parachute deployment and the height of seat trajectory. To meet this stringent time requirement, a completely automatic system is used—a lap belt and shoulder harness which opens automatically 1 sec after seat ejection. Upon separation of the occupant from the seat, an aneroid timing device deploys the parachute in 1 sec if the occupant is below 15,000 ft. The total time consumed is a minimum of 3 sec—1 sec each for lap belt opening, seat-man separation and parachute deployment. If the seat is ejected at a velocity that does not permit slowing down to a safe parachute deployment speed within this time, the parachute may be damaged, resulting in fatal ground contact velocities. If time delays are increased, the extremely low altitude ejections will be fatal, because the man will hit the ground before parachute deployment.

The answer to this dilemma lies in providing a seat trajectory sufficiently high to allow greater time delays between ejection, parachute deployment and ground contact.

Fin Clearance

As airspeeds continue to climb, the problem of raising the seat-man mass to a sufficient height to clear the fin is one of major concern to the escape engineer. Designers have, on occasion, sought to eliminate the fin clearance problem by the use of downward ejection seats. Operational experience (1)[3] indicates the majority of emergency ejections occur at extremely low altitudes. Since the ability to eject at ground level is mandatory, the advantages of upward ejection should be seriously considered before employing downward ejection.

If high seat trajectories are obtained to satisfy the low altitude ejection requirement, then fin clearance will not exist as a significant problem. To obtain high seat trajectories, high ejection velocities are inferred.

Tumbling (Seat Instability)

Aerodynamically stable ejection seats are a must. A tumbling seat reduces the human occupant's tolerance to accelerations induced by windblast. If violent enough, tumbling alone can produce loadings on the occupant that are beyond human tolerances. It is safe to state that any tendency for the seat to tumble or gyrate in any direction will reduce the maximum speed for safe ejection. Not only must the seat be stable in free flight, it must also be launched into the airstream in its trim position without residual rotational velocities (rotational kinetic energy). These requirements are paramount for a satisfactory free flight.

Windblast

As the ejection seat enters the free airstream surrounding the aircraft, the occupant is immediately subjected to forces generated by this moving air. The greatest of these forces is drag, which acts parallel to the airstream, decelerating the seat-man mass immediately upon separation from the aircraft. Fig. 1 indicates the magnitude of the peak, or initial drag force, imposed on conventional seat configurations at sea level airspeeds up to 1000 knots. It is noted that a seat of average configuration ejected at 600 knots would sustain an initial deceleration of about 38 g. The seat-man mass would immediately start losing forward velocity. Drag would also

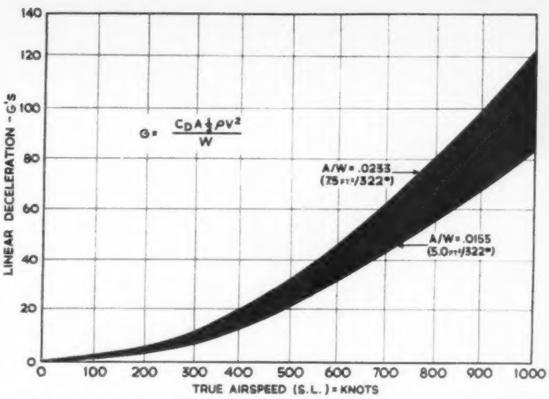

Fig 1 Peak deceleration of conventional seats at various airspeeds

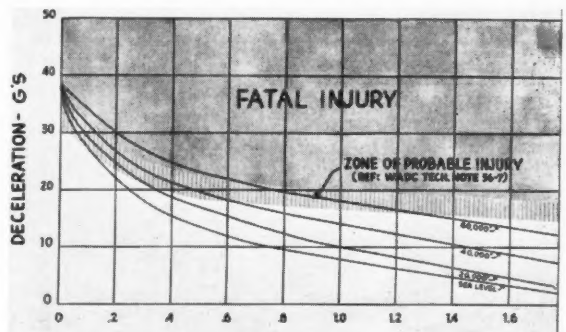

Fig. 2 Acceleration time history at various altitudes for V = 600 knots (EAS)

reduce. The decay of this drag force, with respect to time, is shown in Fig. 2. Note that as altitude is increased, the time duration of the deceleration is also increased. This is accounted for by the fact that the initial velocity of the seat must be greater in the lighter air at higher altitude, if the initial air loading of 38 g is to remain. At these greater velocities, the seat possesses more kinetic energy and requires greater time for the energy to be dissipated. Superimposed on these curves are human tolerances to transverse deceleration as defined by Goodrich (2).

If the ejection seat is aerodynamically stable, this drag force is the primary concern in establishing maximum speed for safe escape. If the seat tumbles, however, then human tolerance to drag forces is reduced, and the seat suffers a great loss in its safe speed capabilities.

A second effect of windblast is commonly termed erosion. Erosion is the result of the local action of windblast on the occupant, inflicting such damage as arm and leg flailing, loss of helmet, torn clothing, face lacerations, tearing and premature opening of the parachute pack, plus a host of others.

Windblast erosion can be reduced by protecting the occupant from full airstream pressures with strategically located windshields, as well as improved personnel flying clothes.

With the exception of windblast erosion, it will be shown that the use of rocket propulsion on an upward ejection seat is an aid in solving the previously discussed problem areas.

Rocket Propulsion for the Ejection Seat

The use of rocket propulsion on an ejection seat was first discussed by the author with Lt. Col. John P. Stapp, Chief of

[3] Numbers in parentheses indicate References at end of paper.

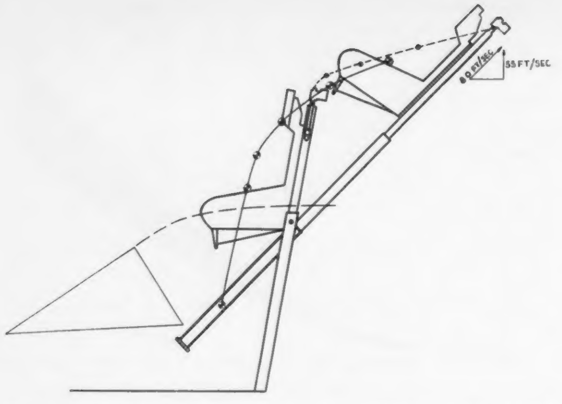

Fig. 3 Seat trajectory at 600 knots (catapult unrestrained)

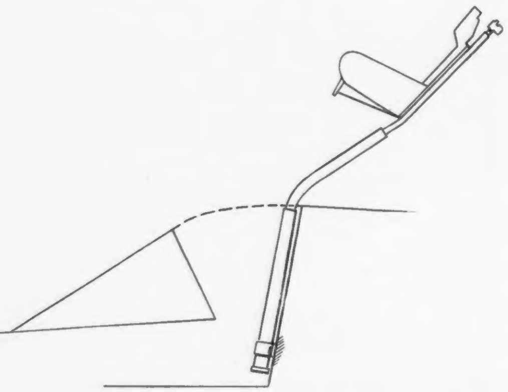

Fig. 4. Seat trajectory at 600 knots (catapult restrained)

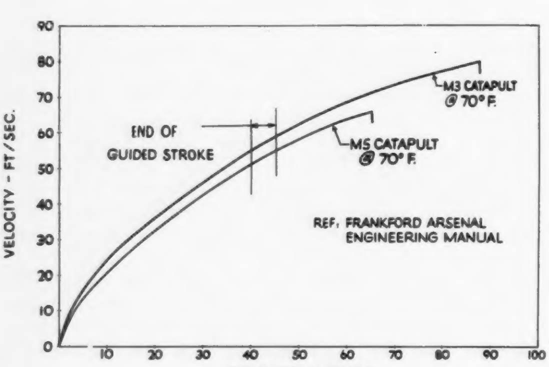

Fig. 5 Relative performance of the M-3 and M-5 catapult

the Aero Medical Field Laboratories, Holloman Air Development Center, N. Mex., in November 1954. At that time rocket power was proposed for use in a horizontal direction to reduce the deceleration, or drag forces, to a tolerable level. Vertical velocities were to be obtained by conventional cartridge catapult. It was largely due to the encouragement of Lt. Col. Stapp that the concept was pursued further by Convair.

Cartridge Catapults

Past attempts by designers to obtain increased ejection velocities had centered around cartridge catapults limited to vertical accelerations of 20 g, applied at a maximum rate of 250 g per sec. With such thrust limitations, the designers concluded that increased ejection velocities could best be obtained by the use of telescoping pistons in a cartridge-powered catapult. James Martin, managing director, Martin-Baker Aircraft Co., Ltd., said in a 1955 lecture before the Isle of Wight Branch of the Royal Aeronautical Society: "To obtain a high ejection velocity with an acceptable pressure curve, there is no substitute for stroke" (3).

The USAF catapult type M-3 has a rated ejection velocity of 80 fps at the end of 88 in. of stroke. In most instances such an ejection velocity would provide satisfactory fin clearance in today's fighter aircraft at speeds where the pilot could survive the windblast. While making a theoretical analysis of seat trajectories in the summer of 1954, it became evident that these high velocities could be approached only if the aircraft could be equipped with ejection rails that provided guided seat travel for the entire catapult stroke. In a fighter-type aircraft, 88 in. of guided seat travel is quite beyond realization without a tremendous weight penalty to the aircraft. In the present generation fighter aircraft, there is probably none that provides more than 40 to 45 in. of guided seat travel.

Fig. 3 illustrates the trajectory of an ejection seat propelled by an M-3 catapult at 600 knots (sea level). If the catapult is restrained at the lower end so that it does not pivot about the mounting trunnion, the piston will bend (see Fig. 4) at speeds sufficiently high to be of concern for fin clearance. This bending of the piston causes severe binding and reduces the final ejection velocity.

Fig. 5 illustrates the relative performance of the M-3 and the shorter stroke M-5 catapult. It will be noted that at strokes of 40 to 45 in., the ejection velocities are approximately the same. By comparing Fig. 3 and Fig. 5, it will be seen that the vertical velocity is no greater at 88 in. of stroke than at 40 in. In comparing the weights of the two catapults, it is found that the M-5 weighs 8.2 lb and the M-3 24.9 lb. The additional 4 fps ejection velocity is obtained at a cost of 16.7 lb (200 per cent weight increase). From September 1955 to January 1956, eight ejections were made from an F-102A nose section mounted on a sled at speeds from Mach 0.30 to 0.99, on the USAF experimental track operated by the Air Research and Development Command at Edwards AFB, Calif. Both M-3 and M-5 catapults were tested and verified the need for improved catapults (4). Catapult piston bending was as expected (see Fig. 6).

Short Stroke Cartridge Catapult

From the analysis made in the summer of 1954, it was concluded that if cartridge catapults were to be used, they must be limited to strokes of no more than 45 in. for fighter aircraft, if the ejection seat was to be properly launched. This meant the thrust values must be increased, and the occupant provided with protection from this increased vertical acceleration. For this task, the able assistance of W. H. Reineking of the Human Engineering Group, Convair (San Diego), was obtained in November and December of 1954. The result was fabrication of several test torso harness vests.

The function of the torso harness is illustrated in Fig. 7. When ejecting the seat-man with accelerations greater than 20 g, the major problem is the compressing force the human upper torso imposes on the lower thoracic vertebra, or upper lumbar vertebra. This force (above 20 g) overloads the vertebral column and pelvic area to the point of skeletal damage. Under vertical accelerations, a significant percentage of the inertia force of the upper torso mass is carried by the torso harness, thus relieving compressive loads from the

lower spine. If the spine were not loaded any greater than 20 times the torso weight, it was concluded that the seat occupant could be safely accelerated vertically at 30 g. These findings were brought to the attention of the Aero Medical Lab, Wright Air Development Center, in the summer of 1956.

Beginning in October 1955, exploratory tests (5) were conducted by Convair with anthropomorphic dummies and human subjects. These tests determined the total load the upper torso imposes on the vertebral column with and without the torso harness. Typical results are shown in Figs. 8 and 9. The feasibility of such a garment was sufficiently demonstrated by these tests to warrant further study and development. Convair has proposed that such a program be conducted, with the aid and guidance of the Aero Medical Laboratory, WADC.

The torso harness holds great possibilities in future seats for both crash protection and increased thrust catapults. If the torso support features are combined with the Navy integrated harness, developed by Douglas, the seat-man harnessing will be tremendously improved. It was evident, however, after the Convair tests of the torso harness, that the development of such a garment, coupled with the necessary sizing and standardization programs, would require a considerable length of time. Attention was then focused on methods of catapulting the seat to greater velocity without exceeding 20 g. The study culminated with the rocket catapult.

Fig. 10 shows early theoretical performance requirements of the short stroke cartridge catapult, as well as the RESCU, Mark I. The RESCU will provide the desired ejection velocity without exceeding the present human limitation on thrust of 20 g. This is possible because extended stroke is utilized. This principle is in agreement with the observation of James

Fig. 6 Bent piston due to restraining the catapult

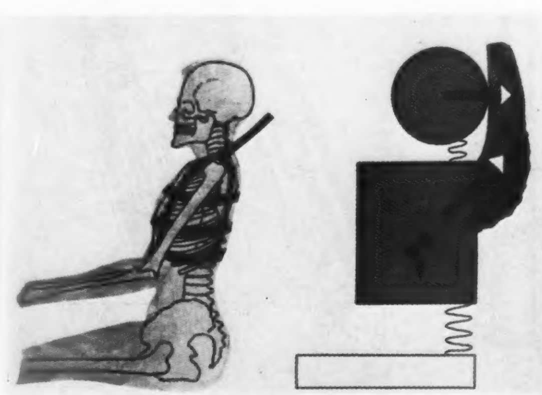

Fig. 7 Function of the torso harness

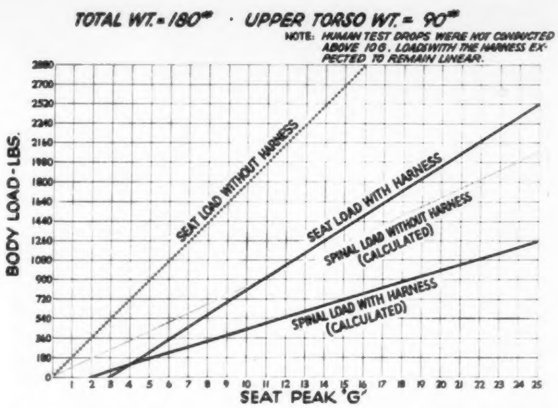

Fig. 8 Induced pelvic and spinal loads with and without upper torso harness

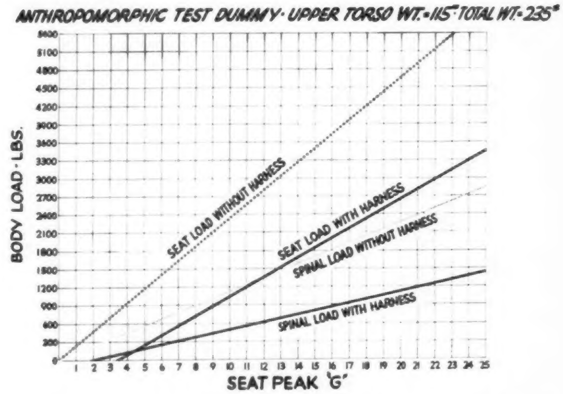

Fig. 9 Human test drops—induced pelvic and spinal loads with and without torso harness

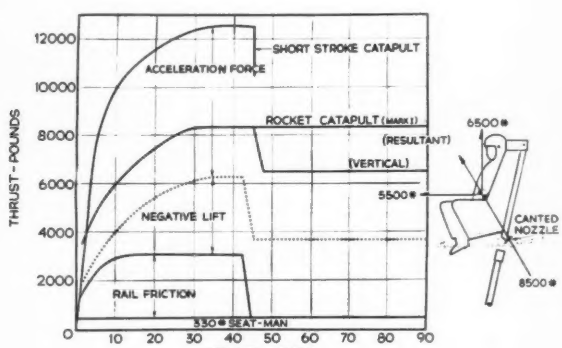

Fig. 10 Required catapult force-stroke

Martin that "there is no substitute for stroke." The initial 40-in. stroke of RESCU still is accomplished by conventional cartridge actuation. As the piston approaches the end of the cylinder, the rocket motor is ignited. The canted nozzle of the rocket causes the thrust vector to pass through the center of gravity and provides both horizontal and vertical thrust to the seat after separation from the aircraft.

Fig. 11 Seats and dummies installed in test nose

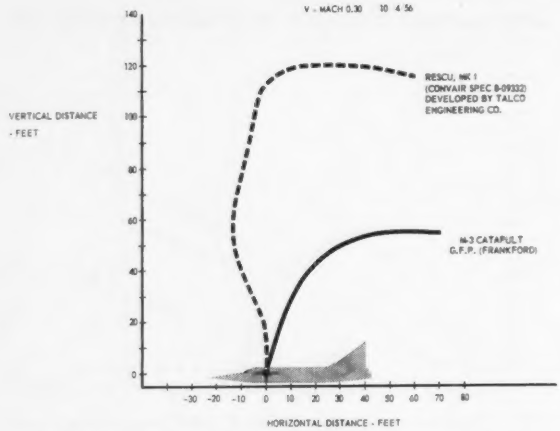

Fig. 12 Trajectories of the two catapults for two sled runs

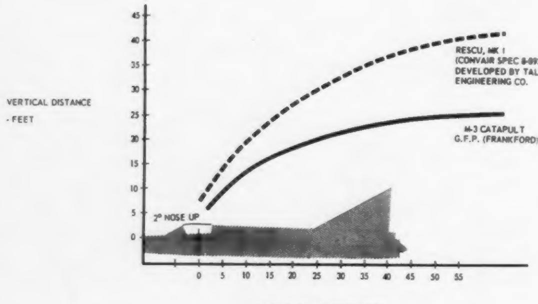

Fig. 13 Trajectories of the two catapults for two sled runs

Development and Testing

Preliminary design performance requirements of the rocket catapult were submitted to WADC in January 1956. In April 1956, Talco Engineering Co., Hamden, Conn., was directed by Convair to proceed with the design and fabrication of test lots of the catapult. Slightly less than six months later, on Oct. 4, 1956, the first firing of RESCU, Mark I, was made from the nose section of a Convair TF-102A traveling at a speed of Mach 0.30 on the Edwards AFB experimental track.

Two seats and dummies, located side by side, were installed in the test nose section as shown in Fig. 11. One seat was equipped with an M-3 catapult, and the other with the RESCU for direct trajectory comparison. The RESCU-powered seat was fired slightly prior to the M-3, so that effects of the rocket blast on the other dummy could be recorded. Comparative trajectories of the two catapults for two of these sled runs are shown in Figs. 12 and 13.

Fig. 14 illustrates the major components of the RESCU. The firing pin A is actuated by gases entering port B. These gases are generated from an initiator fired by the seat trigger mechanism. The firing pin is driven into the primer cap and ignites the cartridge grain C. As gases from the burning cartridge fill the catapult chamber D, the unlocking piston E is moved down permitting the lock fingers F to release the catapult piston G from the cylinder H. The gas pressure then propels the piston up and out of the cylinder. As the base of the piston approaches the end of the cylinder, an interference fit I decelerates the piston head J to a stop. The inertia forces of the piston shear the flange head ignition plug K. Removal of the ignition plug allows gases from the catapult chamber to enter the rocket tube, igniting the rocket grain L. The rocket gases are vented through the canted nozzle M.

The firings of the RESCU, Mark I, from the TF-102A cab at speeds ranging from Mach 0.30 to 0.98 indicate that the single piston and canted nozzle arrangement offer improvements in the four major problem areas previously discussed:

Low Altitude Ejections. Because of the greater time of thrust (increased stroke), the vertical ejection velocity is increased. This provides increased height of seat trajectory essential for low altitude, high speed ejections.

Fin Clearance. The increased vertical velocity also will permit fin clearances at greater airspeeds.

Tumbling. The relatively short piston permits catapult separation before the seat leaves the aircraft rails. Such a condition results in a minimum of eccentric loadings on the seat as it leaves the aircraft. With the rocket thrust vector acting through the seat-man center of gravity after seat-aircraft separation, the added thrust impulse does not produce tumbling.

Windblast. The horizontal thrust vector of the canted nozzle subtracts 15 g from the magnitude of the peak wind-

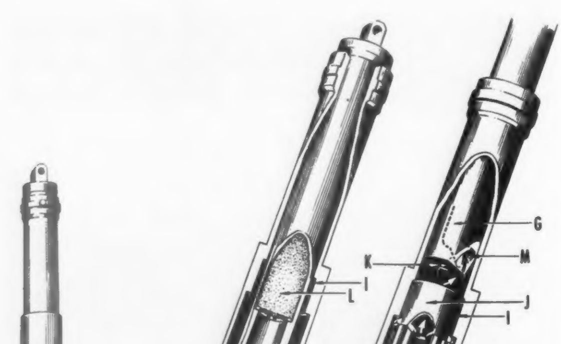

Fig. 14 Major components of RESCU Mark 1

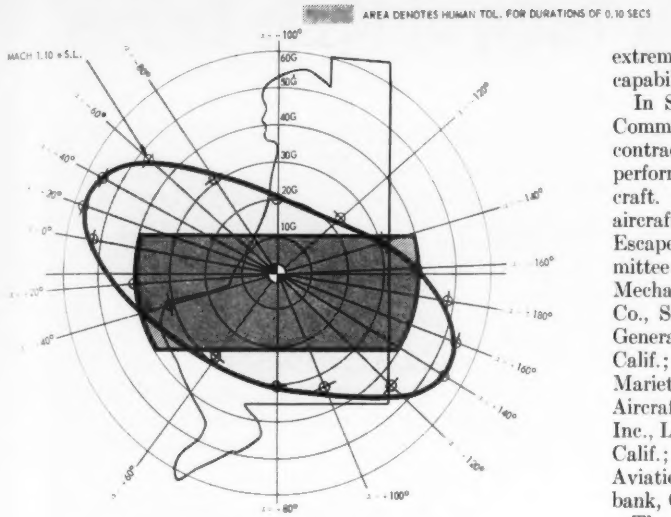

Fig. 15 Magnitude and direction of peak air load

blast deceleration. This reduction in peak deceleration costs time, and the occupant will be subjected to the effects of windblast erosion for a greater time period.

Future Designs

Much work remains to be done to develop the ultimate performance of ejection seats. Windblast erosion protection must be provided by design improvements in the personal equipment and the seat structure. Seats of lower drag configurations must be developed, and the optimum attitude of the seat upon ejection must be investigated. Fig. 15 indicates that even seats of current high drag configuration may be ejected at angles of attack (a) of +50 or −140 deg at a supersonic speed of Mach 1.10 (sea level) without imposing excessive peak g on the occupant (6–9). If these features are combined with higher thrust rockets, the maximum speed for safe ejection may be greatly increased. Higher thrust rockets are conceivable when the torso harness is used.

Every effort must be made to provide safe escape for aircraft with speeds in excess of human tolerances using ejection seats, which must be made to serve until a suitable escape capsule is developed. The capsule is still some distance in the future. Obvious advantages exist in the use of a capsule at extreme altitude, but stabilization and ground level ejection capabilities have not yet been sufficiently developed.

In September 1956, the Air Research and Development Command requested the major aircraft companies having contracts with the Air Force to jointly develop an increased performance ejection seat for all "century series" fighter aircraft. This move received the wholehearted support of the aircraft industry, and on Oct. 9, 1956, the Industry Crew Escape System Committee (ICESC) was formed. The committee is composed of 14 major aircraft companies: Aircraft Mechanics, Inc., Colorado Springs, Colo.; Boeing Airplane Co., Seattle, Wash., and Wichita, Kans.; Convair Div. of General Dynamics Corp., Fort Worth, Tex., and San Diego, Calif.; Lockheed Aircraft Corp., Burbank, Calif., and Marietta, Ga.; The Martin Co., Baltimore, Md.; McDonnell Aircraft Corp., St. Louis, Mo.; North American Aviation, Inc., Los Angeles, Calif.; Northrop Aviation Co., Hawthorne, Calif.; Republic Aviation Corp., Farmingdale, N. Y.; Stanley Aviation Corp., Denver, Colo.; Weber Aircraft Corp., Burbank, Calif.

These companies are exerting concerted effort to develop in the shortest possible time an ejection seat system capable of safely ejecting an air crew man at supersonic speeds. The author sincerely believes the development of the RESCU unit will prove to be of significant value to the ICESC in the accomplishment of its task.

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Supersonic Rain Erosion Testing of Missile Radomes

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and

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Mach 2.0 Track Test Vehicle

Historical Background

SINCE the advent of high speed aircraft and missiles, the damage to radomes and other parts from rain has become a problem requiring understanding and solution. Anticipating that this problem would become more important with increases in flight velocity, the materials laboratory of WADC sponsored a study of rain erosion testing techniques. One part of this study was undertaken by the Convair thermodynamics laboratories in 1952 and has continued since that time. A small group of engineers, under the direction of W. L. Dittmann, has been obtaining data on rain damage to radomes and radome materials at ever-increasing flight velocities. A large part of their task is to find methods that will accelerate the sample materials to high velocity without damage and with high probability of intact recovery.

The first supersonic testing of materials was accomplished with a 20-mm aircraft cannon. Test specimens were mounted in the nose of a modified projectile and fired horizontally through 500 ft of simulated rainfall. Upon firing, a tracer element in the projectile was ignited and burned approximately $\frac{3}{4}$ sec. A black powder charge then expelled the test specimen and parachute. The parachute checked the forward velocity of the test specimen within 10 ft and intact recovery was made. Speeds up to Mach 3.0 have thus been obtained. More recently, a 57-mm cannon was obtained. This increased the size of the test specimen to 2-in. diam.

Data obtained from these studies show that erosion damage is a function of velocity, shape, material, water drop size and the distance the water drop must travel in the flow field aft of a shock. Thus, erosion damage obtained on an object with a 2-in. base diam will only simulate the damage to an equivalent nose portion of a corresponding larger specimen. The only method of obtaining quantitative results of rain damage to the total surface of a shape of much larger diameter is to test full scale. This was done by mounting full-scale radomes on a rocket sled and firing through a simulated rainfall.

Rocket Sled Design

The design of a Mach 2 rocket sled was undertaken by the Convair thermodynamics laboratory. The requirements establishing design criteria for the vehicle were:

1 Peak velocity should be Mach 2. This velocity was chosen so that correlation could be made with the ballistics studies.

2 Test specimens should be radomes of approximately 30-in. diam and weigh 100 lb.

3 Longitudinal accelerations during that part of the run in which rockets are armed or burning should be limited to ± 30 g. This limitation was imposed by the solid propellant in the available rockets.

4 Peak velocity of the test vehicle should be obtained within 4600 ft. This was the approximate center of the rainfall range installed at the AFFTC track for the original sled.

5 The test vehicle should be stopped by means of a water brake beginning at 8200 and extending to 10,000 ft.

The first step in the design procedure was a study of configurations that would most likely fulfill the test requirements with consideration given to aerodynamic conditions and Edwards AFB track requirements.

From the failure of the first high speed sled, it was obvious that at high speeds the choking of flow under any area at track level gave rise to large lifting loads. This, then, would require the primary structure of the sled to be open or the structure at track level to have minimum horizontal dimensions.

Since track rails at the AFFTC are not continuous, rail joints exist every 39 ft. The length of the sled between slippers must not be a multiple of rail joint spacing. The sled must also be long enough so that slipper reactions resulting from loads and moments acting on the sled are not excessive.

Many configurations were studied but the aerodynamic advantage of seven rockets clustered behind the radome was chosen as presenting minimum drag area. The rockets available were Aerojet 2.2 KS of 11,000-lb thrust and 2.2 sec burning time. Rocket diameter is approximately 11 in., length 52 in., loaded weight 265 lb and burn-out weight 122 lb. This arrangement would make a compact power package of 77,000-lb thrust.

With this configuration and the longitudinal acceleration limited to 30 g, the minimum structural weight of the sled could be determined.

$$\begin{aligned} F &= MA \\ 77{,}000 &= (\text{structure wt.} + \text{rocket wt.}) \times 30 \\ 77{,}000 &= (\text{structure wt.} + (7 \times 265)) \times 30 \\ \text{structural wt.} &= 701 \text{ lb} \end{aligned}$$

Calculations based on this weight and an assumed drag curve showed that the required velocity could not be obtained without a pusher sled to provide initial acceleration. Step-by-step, velocity calculations were undertaken for pusher and sled combinations to determine the pusher weight and thrust that would accomplish the required initial acceleration. These calculations showed that a 300-lb pusher vehicle with five rockets, 2.2 KS-11,000, would accelerate the test vehicle to 900 fps in 1000 ft. Light-off of the seven rockets on the test vehicle at this point would then accelerate it to 2134 fps (M 1.9) at station 4532. Water brake entry at station 8200 would be at 800 fps.

Since no test vehicle had operated at ground level at this

Presented at the ARS Spring Meeting, Washington, D. C., April 4–6, 1957.

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high Mach number and been recovered, little drag data were available. A conservative estimate of drag used in design was 63,000 lb at $M = 1.9$. A lower drag would mean a higher peak Mach number, but also a high water brake entrance velocity. This was tolerable.

The design problem now was to design the structure to the required weight and to withstand the loadings imposed.

The Edwards AFB experimental track had suggested a minimum length of 11 ft for the sled, and later, at Convair's request, allowed a 9-ft minimum. Since structural loadings would be high and the rocket blast would impinge on the aft structure, SAE 4130 Chrome-Moly steel was chosen for all primary members.

Conventional rocket sled design would have resulted in a test vehicle of prohibitive weight. The water brake assemblies of existing sleds weigh up to 350 lb and conventional slipper weights are 50 lb per slipper.

To utilize all members to full structural advantage, it was decided that the water brake should become a structural member and as lightweight as possible. This was accomplished by integrating the water brake turning sections with the main and rear cross beams. The turning sections were $\frac{1}{8}$-in. wall 160 deg ducts of 6-in. OD.

The scoop then became an integral part of the main beam. Since tubular sections were used in the water brake turning section, the design progressed to the use of 6-in. diam 0.187 in. wall tubes for the main frame beam and front crossbeam. A composite main frame beam was fabricated by splitting the tube and welding a shallow V-plate top and bottom. To conserve weight the tube was taper turned before splitting, reducing the section modulus to the design point.

Water brake entry velocity up to 1000 fps was not considered critical and loadings from water brake deceleration were less than acceleration or set-back loads. After the design length was shortened from 11 to 9 ft, the deflection of the main beam at the water scoop inlet was calculated to be 0.196 in. and this was considered reasonable. A dynamic analysis of response to this loading was not made before the first run and we shall see that this was the most critical design point.

Extensive stress analysis and much modification went into the structure containing the seven rockets and mounting the test specimen. The thrust load must accelerate the main frame on which it is mounted which is 75 per cent of the structure weight. The drag distribution was such that 60–70 per cent of the total drag was felt by the lower structural members. Moments acting from suddenly applied loads when the rockets fired and at burnout must be transmitted to the main frame. The original skeletal pod structure was sheathed with aluminum shear panels to provide the necessary stiffness and strength.

One serious load application was the interference lift of the radome. This lifting load was calculated to be 10,000 lb at Mach 2.0 with the radome an ogive 100 in. long. Serious consideration was given to pitching the radome axis down 5 deg to counteract part of this lift load. Analysis of all the loads on the structure showed that the lift load with the radome axis horizontal reduced the resulting moments acting at critical sections but made the front slipper reactions higher which was more tolerable.

Design loads used are illustrated in Fig. 1.

Nearly all rocket sleds operating at the Edwards track use 18-in.-long slippers which are pinned to the structure to allow articulation. The weight of such slipper assemblies is 50 lb each. For the Mach 2.0 sled it was felt that articulation of the slipper would be of no advantage since the slipper would not have time to respond to track irregularities. The weight saved by designing a fixed slipper was approximately 25 lb per slipper.

Inserts are used in each slipper to provide a wearing surface that can be replaced after one or more runs. To date, the most practical insert material has been Type 321 stainless

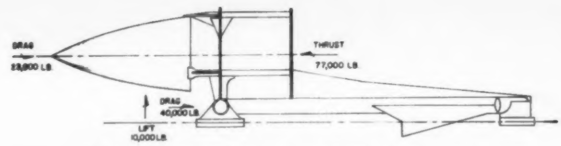

Fig. 1 Design loads at peak velocity $M = 2$

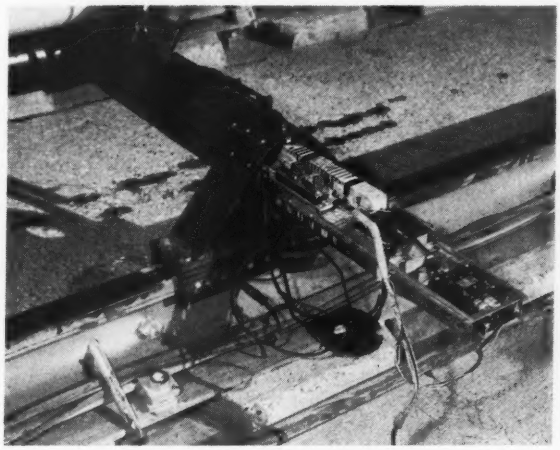

Fig. 2 Instrumentation installation

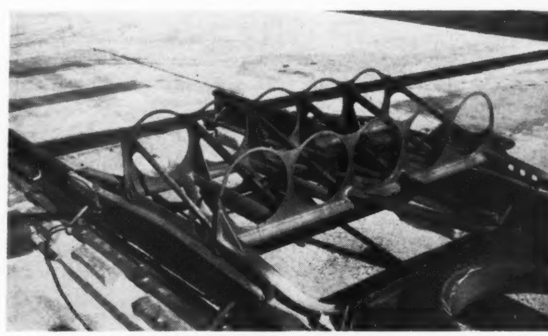

Fig. 3 Pusher structure

steel. Since little is known of friction at very high velocities, it was decided not to experiment with insert material but to use 321 stainless. It is our opinion, however, that much work should be done in determining how insert wear is related to velocity and specific pressure.

The erosion testing of radomes did not require telemetered information from the rocket sled. Since it was decided to approach the maximum velocity in increments of $M = 0.25$ starting at $M = 1.25$, instrumentation of the sled structure during these runs would check design points. After the Mach 2.0 velocity was attained, the instrumentation package could be removed to reduce weight. The simplicity of the structure left little room for a telemeter package but one was designed to fit into the 6-in. tube serving as the front crossbeam. This was an eight channel transmitter weighing 18 lb (see Fig. 2).

The design of the pusher vehicle, illustrated in Fig. 3, was straightforward. A tubular structure using 2-in. SAE 4130 tubes of 0.109-in. wall was the basic framework. The end frames were fabricated to mount the slippers with a center line distance between slippers of 60 in. Twelve-in.-long

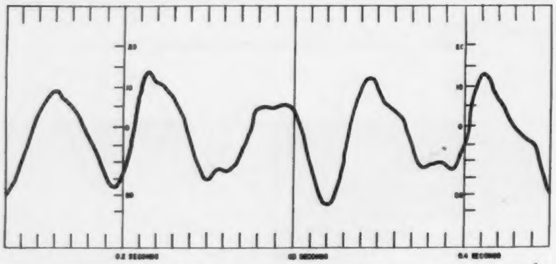

Fig. 4 Vertical accelerometer trace located at radome center of gravity

Fig. 5 Test vehicle

slippers were used because both the velocity and loadings were relatively low. Originally the design called for two pusher contact points at the front slippers, but a check of loadings showed that the stress in the sled water brake tubes was marginal. A center pusher beam was added. This beam carried the thrust load of the pusher sled into the center tube, thus reducing the loading in the water brake tubes.

Fabrication of this design was accomplished in the thermodynamics laboratory experimental shop and the completed test vehicle was shipped to the AFFTC high speed track in late January 1956.

Prerun inspection and design checks at the AFFTC revealed necessity for strengthening rocket retainer lugs. This work was accomplished and within 90 days the test vehicle was operating at Mach 2.0.

Operation

The operation of a supersonic vehicle on a high speed track presents many problems centered around these velocities. Some of these problems in order of their importance are (a) slipper insert wear, (b) water brake operation and (c) rocket ignition.

It has been mentioned that fixed slippers were installed on the test vehicle at a considerable weight saving. This installation presented a problem of slipper alignment with the rails. The track alignment was checked prior to the first test and found to be 0.10 in. out of alignment laterally thus negating the 0.060-in. slipper clearance on each side of the rail. The rails were then roughly realigned to provide proper clearance.

In the original design of the slippers it was determined that $\frac{1}{4}$-in.-thick 321 stainless steel inserts would be satisfactory for operation. Later testing at high Mach numbers resulted in more than expected wear on the lip inserts because of the high lift loads, and indicated the requirement for thicker inserts. The slipper sides were then lengthened to allow clearance for $\frac{3}{8}$-in.-thick lip inserts to provide bearing material for a longer period of time. The wear on the other inserts in the slipper did not warrant using thicker inserts, and since weight was at a premium they were left unchanged.

Although operation of the test vehicle at speeds of Mach 2 and above caused extreme wear of the 321 stainless inserts used in the lips of the slippers (inserts being completely worn out), it was never felt that a definite danger existed in the accomplishment of the tests.

Although no solution was found to provide more satisfactory inserts, much information was gained concerning insert wear. Flame patterns from insert "burning" could be seen extending over 9 ft behind the slippers. These flashes would almost completely disappear with the entry of the test vehicle into the rain range. Analysis of this information leads to the belief that the test vehicle is actually running on a molten layer of metal acting as a liquid lubricant.

As mentioned, the most critical design part of the test vehicle was the main beam. Although this beam was sufficiently strong to withstand the applied loads, the problem lay in its flexture when these loads were applied in the water brake area. The design section of this paper states that the water brake inlet scoop was installed under the center portion of the main beam. When this scoop enters the water, the applied down load caused the beam to deflect downward; this in turn caused a higher braking load and consequently more deceleration. Under this high deceleration the large mass of the rocket package in the forward section of the vehicle caused the beam to deflect up. Thus, a high forcing function is developed, causing a first bending mode resonant oscillation of the main beam structure. This can be seen from the trace of a vertical accelerometer mounted at the center gravity of the radome (Fig. 4).

Since these resonant vibrations caused a large movement (approximately 1 ft) at the end of the radome due to the 9-ft lever arm, several structural modifications were made in order to stiffen the main beam and reduce these oscillations. These modifications were (a) addition of a vertical stiffener down the top of the main beam from the rocket pod to the rear crossmember; (b) shortening of the radome by 2 ft and strengthening of the radome mounts; and (c) addition of stiffeners on the side of the water brake inlet.

These modifications, although not completely eliminating the resonant oscillations, reduced them to a small enough value so that they were not considered dangerous. The addition of weight of the modifications was almost compensated for by reducing the length of the radome. The final weights of the main sled and pusher sled (without rockets) and instrumentation were: (a) Main sled, 796 lb; (b) pusher sled, 325 lb; and (c) instrumentation (eight channels), 25 lb.

The firing weight of the test vehicle (Fig. 5) will vary as much as 25 to 30 lb depending on instrumentation installation and rocket tolerances.

The final and most easily solved problem encountered during this program so far as operation was concerned was ignition of the second stage rockets on the main sled. With velocity at the end of the pusher stage 1000 fps and the firing screen box only 1 ft long, only 0.001 sec was available to complete ignition.

It was determined that this allowed insufficient time to discharge the 900 volts used through a condenser and insure 100 per cent reliable ignition. The solution consisted of installing two separate screen boxes within 3 in. of each other to insure second-stage ignition.

Performance

The first run on the supersonic rain erosion vehicle was accomplished on Feb. 1, 1956, when a velocity of Mach 1.2 was attained. Successive trial runs were accomplished at Mach 1.5 and 1.75. On April 24, 1956, Mach 2.05 was attained and established a new world's speed record for a recoverable vehicle. The ensuing six runs were at velocities above Mach 2, with a maximum of 2459 fps or Mach 2.15 (Run No. 12)—the highest velocity ever attained for a recoverable test vehicle on a high speed track.

The maximum accelerations achieved during this program were 12 g during the pusher phase of operation, and 29 g during the main stage. Upon burnout of the rocket motors a maximum deceleration of 26 g occurs due to air drag. Entry into the water brake occurs at Station 8250 in an area of small change in gradient in order to reduce the amount of braking force achieved at high velocity. A maximum deceleration of 14 g occurred in the water brake area giving a braking load just under 20,000 lb. Entry into the water was at a velocity of approximately 1000 fps and recovery was effected in an average distance of 1750 ft, or at approximately Station 9900.

The firing weight of the pusher and main sled combination was 3300 lb with the burnout weight of the main sled being 1660 lb. The pusher vehicle was equipped with a splash-type brake which entered the water at Station 8000 and effected recovery within 1200 ft.

The maximum achieved braking load of 20,000 lb was much less than anticipated during the design stage. The maximum design load for the water brake was 50,000 lb. By careful selection of the water brake entry point both the maximum water brake loading and the ever-present resonant vibrations were kept to a minimum to maintain a satisfactory factor of safety for the system.

Conclusion

The operation of the supersonic rain erosion test vehicle at the AFFTC track was highly satisfactory, with a total of seven tests being accomplished above Mach 2 and six tests being accomplished above Mach 1.80.

All nineteen runs with the exception of one misfire were accomplished at velocities in excess of Mach 1.2.

Much valuable information has been gained during this series of tests concerning slipper insert wear. In the AFFTC track experience this was the first time a serious slipper insert problem was encountered and knowledge gained from this experience has brought more recognition to, and provided a better understanding of, the insert wear problem.

The original velocity requirement, which was set up at the beginning of the test program, was to obtain Mach 2 for 0.5 sec. This would produce a sustained velocity through the then installed 1200 ft of artificial rainfall range. A later increase in the length of the rainfall system brought the total length to 2100 ft extending from Station 3800 to 5900.

Although the test velocity was not quite constant because of the higher than anticipated drag loads, an average velocity of 2300 fps was attained through the 1200-ft system of Mach 2.07 and an average velocity of 2142 fps or Mach 1.93 resulted through the 2100 ft section. Thus, the original requirement was achieved and although a lower Mach number was achieved for the 2100-ft system it was close enough to be satisfactory.

The challenge of routine operation of a Mach 2 vehicle has been met and solved and the sled preparation and post-run inspection time reduced after every successful test.

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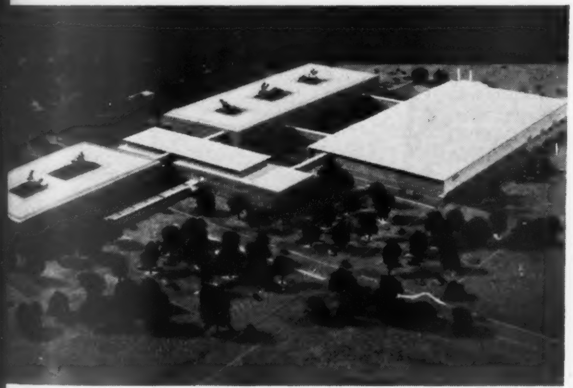
Dr. Peter J. W. Debye, professor emeritus of chemistry at Cornell University, and Dr. Lloyd P. Smith, President, Avco Research and Advanced Development Division, discuss the Avco research program prior to Dr. Debye's recent colloquium at the Division's Lawrence, Massachusetts, headquarters.



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Book Reviews

Ali Bulent Cambel, Northwestern University, *Associate Editor*

Scientific Uses of Earth Satellites, edited by James A. Van Allen, University of Michigan Press, 1956, 316 pp. $10.

Reviewed by H. FRIEDMAN
U. S. Naval Research Laboratory

Thirty-three papers present a comprehensive picture of the problems of observing and instrumenting artificial satellites for research. Five papers are concerned with visual acquisition and determination of the orbit, the perturbing effects of sun and moon, the oblateness of the earth and atmospheric drag. Three papers treat the general subject of components, systems and environment for satellite instrumentation. The remaining papers are descriptions of proposed scientific experiments.

The papers were originally presented on Jan. 26 and 27, 1956, at the tenth anniversary meeting of the Upper Atmosphere Rocket Research Panel at the University of Michigan. The proposed experiments represent the first enthusiastic response of American scientists to the challenge of utilizing an artificial satellite for scientific research.

The determination of air density from the drag on the satellite will be one of the major objectives of the tracking program. This problem is discussed thoroughly in papers by Lyman-Spitzer Jr. and by R. J. Davis, F. L. Whipple, and J. B. Zirker. Present plans for instrumenting the satellite include five approved experiments: (1) Lyman alpha radiation and environmental measurements, (2) cosmic ray observations, (3) measurements of the earth's magnetic field, (4) radiation balance of the earth and (5) cloud cover measurements. Four of these are decribed in considerable detail in individual papers. The single omission is the fourth experiment on earth radiation balance.

Many papers deal with experiments that could not be included in the first group of six satellites because of the severe weight and power limitations. But these proposals present interesting possibilities for future satellites with greater payload possibilities.

The papers are technical, yet not too highly specialized to discourage the reader interested in obtaining a general survey of this realm of scientific exploration.

Properties of Combustion Gases, System C_nH_{2n}-Air. Vol. I: Thermodynamic Properties. Vol. II: Chemical Composition of Equilibrium Mixtures, by H. N. Powell, S. N. Suciu and S. R. Brinkley, McGraw-Hill, New York. Vol. I, 377 pp.; Vol. II, 677 pp. $75.

Reviewed by ALLAN SCHAFFER
The Ramo-Wooldridge Corp.

These two volumes of tables are an outstanding contribution to combustion science and practice. Only the well-known charts by Hottel, Williams and Satterfield have a comparable scope. The present tables give both equilibrium thermodynamic properties and chemical compositions for the products of combustion of a typical jet engine fuel with air over a wide range of variables. The tables were originally published for internal use by the General Electric Co.

Thermochemical computations for hydrocarbon-air reactions are complicated by molecular dissociations above about 3000 R and involve the solution of sets of simultaneous nonlinear algebraic equations. In the past, dissociation phenomena have often been ignored to simplify the calculations despite the fact that appreciable errors were so incurred. Digital computers have made feasible the large-scale calculational program necessary in preparing the present tables. The basic molecular data for the computations have been taken from the National Bureau of Standards tables.

There are generally four independent variables in hydrocarbon-air combustion calculations, namely, temperature, pressure, equivalence ratio and the hydrogen-carbon ratio of the fuel. The ranges of interest for the first three variables are completely covered in the GE tables, but only fuels with an H/C ratio of two are treated. The independent variable grid is: Temperature from 600 to 5000 R in 100 R increments, pressure from 0.01 to 30 atm in 22 increments, and equivalence ratio from 0.25 to 4.0 in 15 increments. On this grid, the following thermodynamic functions of the products of combustion are listed: Enthalpy, entropy, mean molecular weight, density, equilibrium sonic velocity, frozen sonic velocity, heat capacity and two nonideality coefficients. Equilibrium concentrations in molfractions are given for the following species: A, C_s(graphite), CO, CO_2, H_2O, O_2, N_2, H, O, N, NO, OH, CH_4 and NH_3. All molfractions greater than 10^{-9} are listed. In addition to the tabulations of mixture properties and compositions, tables are given of the enthalpy, Gibbs free energy, entropy, and heat capacity functions for the above pure species over the range 600 to 5000 R.

Enthalpies are given on an absolute basis and include heats of formation as well as sensible heats. It has been recognized for some time that the use of absolute enthalpies greatly simplifies thermochemical calculations. However, the choice of the enthalpy reference state is arbitrary, and a variety of states have been selected by different authors. The result is that data from these different sources cannot be freely interchanged. A "standard" reference state is needed. The authors have adopted what this reviewer believes to be the least arbitrary reference state. Each element of interest is assigned for its normally stable form a value of zero enthalpy at 0 R. Let us hope that this reference state will be adopted for all future combustion computational programs.

In addition to the tabulated data, the authors have included a 45-page introduction in which they discuss combustion calculations, derive pertinent equations and solve illustrative examples. This

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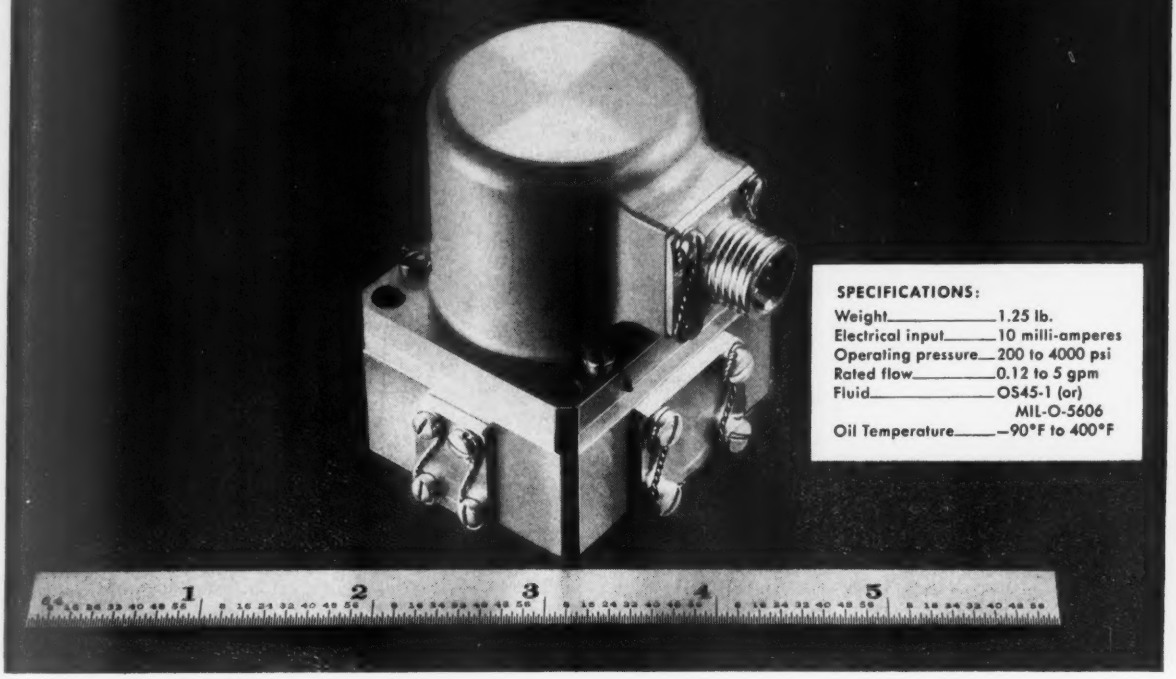

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introductory section is very well written. It serves not only as an explanation of the tables but also as a brief text for combustion analysis. The authors point out that in applying the perfect gas law to combustion products, one must allow the molecular weight of the gas to be a variable, a function of both temperature and pressure, due to molecular dissociations. These effects are conveniently treated by introducing two nonideality coefficients. The importance of the dissociation equilibria in any regime is indicated by the magnitudes of the nonideality coefficients, which are listed in the tables along with other properties of the combustion products.

Graphical procedures for performing analyses are recommended by the authors. Illustrative examples of first law problems, such as the calculation of adiabatic flame temperatures and theoretical heat releases, are solved by means of an enthalpy-fuel/-air ratio diagram. A typical afterburner problem is also worked out with this general plot. Second law problems, such as nozzle expansions, are solved by means of a Mollier diagram. It is of interest that equilibrium nozzle expansions in which the specific heat ratio of the gas is not constant can be treated easily.

The previous discussion has indicated the tremendous scope of these volumes. Few criticisms (except for the price) can be made. One wishes that data for pure air had been included, but compatible air data are available from other sources. The principal criticism is that only one H/C ratio has been considered. It is true that $H/C = 2$ is closely representative of kerosene-type aviation fuels as well as gasolene fuels and is exactly applicable to the pure fuel species ethylene. But one wonders about using the tabulated data for fuels with H/C ratio other than 2. The authors make no statement in the text about the sensitivity of the results to the H/C ratio because at the time of the writing they contemplated a series of volumes for different H/C ratios. However, the goal was never realized and only the $H/C = 2$ computations and a limited amount $H/C = 3$ computations were made. Enthalpy data for $H/C = 3$ have subsequently been published (see ASME paper 56-SA-68).

This reviewer has attempted to find out over what range of H/C ratios the present volumes may be used without incurring excessive error. In private correspondence, the authors stated that, in agreement with previous estimations by Hottel, Williams and Satterfield, they have found that variations in gross mixture properties with H/C ratio are small in the range 1.7 to 2.4. This reviewer compared results from the $H/C = 2$ data with some selected published computations for propane, which has $H/C = 2\frac{2}{3}$, and found errors in flame temperatures of about $3\frac{1}{2}$ per cent and in compositions of about 5 per cent. In view of these results, one might still expect errors of several per cent in the 1.7 to 2.4 H/C range.

With the calculational program all written and the techniques established, it seems a shame that there are no plans to extend the computations over a suitable H/C grid. Some agency could do combustion science a service by insuring that this program is carried out.

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Jet and Rocket Propulsion Engines

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Editor's Note: Contributions from E. R. G. Eckert, J. P. Hartnett, T. F. Irvine Jr. and P. J. Schneider of the Heat Transfer Laboratory, University of Minnesota, are gratefully acknowledged.

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Aerothermodynamic Staff members discuss heat flux during reentry of a hypersonic vehicle. Left to right: J. I. Osborne, aerodynamics; R. G. Wilson, thermodynamic research; W. E. Brandt, thermodynamic analysis; Dr. L. H. Wilson, Thermodynamic Section head.

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The Test Equipment Engineer is engaged primarily in the design of specialized missile check-out equipment. As missiles push the state of the art, test equipment must exceed the missiles in precision and reliability. Automatic programing, go-no-go evaluation, and automatic data processing add up to automation in missile testing.

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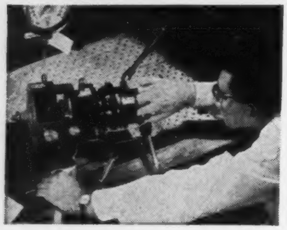

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Two Steering Intelligence Engineers discuss space allotment in a new guidance component. This close association of engineers with the "flying" equipment is typical of the Steering Intelligence Section. Engineers in this section are primarily and *directly* concerned with refining the guidance equipment to steer the missile with greater accuracy, at greater ranges and with simpler and more reliable electronic equipment and, consistently, with minimizing the cost. Work is actively in progress in every principal field from microwave equipment to inertial end instruments.

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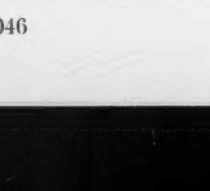

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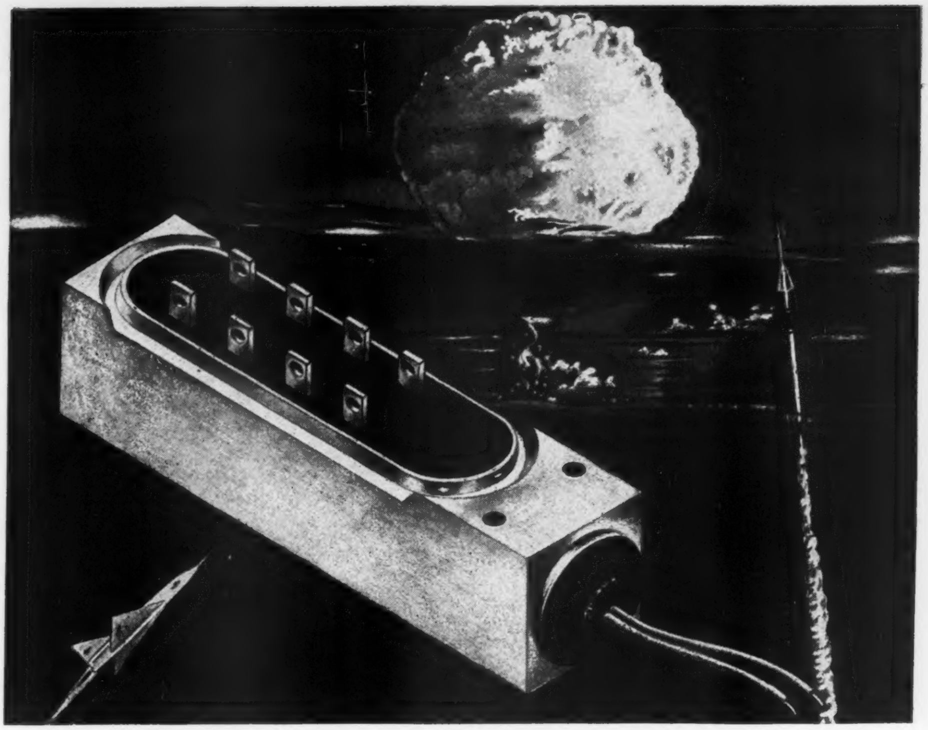

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- Switch Actuation Time*: Less than 5 milliseconds

*Actuation Times as short as 0.1 millisecond and as long as 20 seconds will be available.

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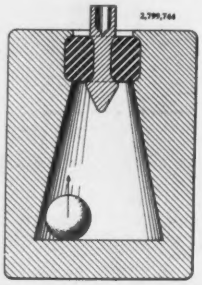
New Patents

George F. McLaughlin, *Contributor*

Rocket launching support structure (2,792,756). Werner Schneiter, Bern, Switzerland, assignor to Society "Brevin A. G."

Sleeve slidably mounted on the body of a rocket for longitudinal guiding. Fins, rigid with the sleeve, limit the sliding of the sleeve on the body between front and rear limit positions. The rear position is the operative position when the rocket is flying on its trajectory.



Switching device for controlling the ignition circuit of an explosive projectile (2,799,744). J. L. Nordgren, Hagersten, Sweden, assignor to Aketiebolaget Bofors.

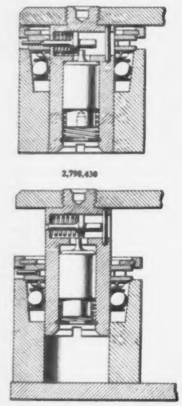
Member with a frusto-conical chamber mounted in the nose of the projectile, with the narrow end facing forwardly. Two electrical contacts in the narrow end and a closing member are movable within the chamber by the effect of the retardation by the projectile in flight.

Variable area jet nozzle (2,793,491). Arthur W. Gardner, Indianapolis, Ind., assignor to General Motors Corp.

Two valves mounted for rotation about an axis transverse to the jet pipe extend over the nozzle to vary the effective area. A seal ring extending around the pipe bridges the space between the pipe and valves. The ring is urged radially outwardly against the interior of the valve by pressure from the jet pipe.

Jet nozzles and jet propulsion units provided with means for deviating the jet (2,793,494). M. Kadosch, F. G. Paris, J. Bertin and R. H. Marchal, Paris, France, assignors to Nationale d'Etude et de Construction de Moteurs d'Aviation.

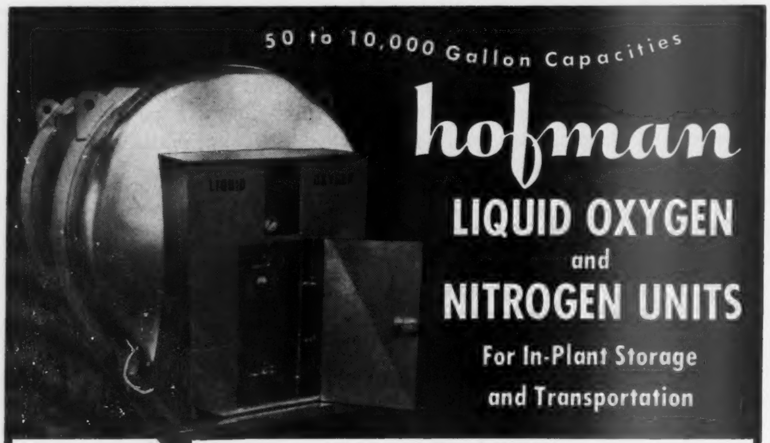
Propulsive nozzle forming an axially flowing jet, and an internal means for deflecting the jet. Guide vanes extend laterally in the path of flow and provide an exhaust curved path so as to form a secondary jet stream at a substantial angle with the axis.



Rocket grain braking apparatus (2,798,430). David B. Grimes, Silver Spring, Md., assignor to the U. S. Navy.

Unit for preventing movement of propellant grains in a rocket. Wedging means in the recess between the housing and an inner member and a detent (releasable by inertial forces upon launching of the rocket), restrict relative movement of the housing and the inner member.

EDITORS NOTE: Patents listed above were selected from the Official Gazette of the U. S. Patent Office. Printed copies of Patents may be obtained from the Commissioner of Patents, Washington 25, D. C., at a cost of 25 cents each; design patents, 10 cents.



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High heat of reaction, other characteristics point to magnesium for high-energy fuels

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- *High heat of reaction*
- *Chemically reactive*
- *High energy per unit volume*
- *High theoretical flame temp.*
- *Can be dispersed in various media*
- *Products of combustion are: inert, relatively non-abrasive and present no toxicity problem*
- *Inexhaustible raw material supply*

Magnesium's heat of reaction, for example, compares to that of other fuel materials as follows: magnesium, 14,200 B.T.U. per lb. of oxygen required for combustion; aluminum, 13,370; lithium, 10,980; boron, 9,670 (all at 1800°K). This plus magnesium's high theoretical flame temperature indicates that magnesium is especially adaptable for short-range applications where high initial thrust is desirable.

In addition, magnesium can also be considered as an intermediate in the manufacture of other metallic and organometallic fuels.

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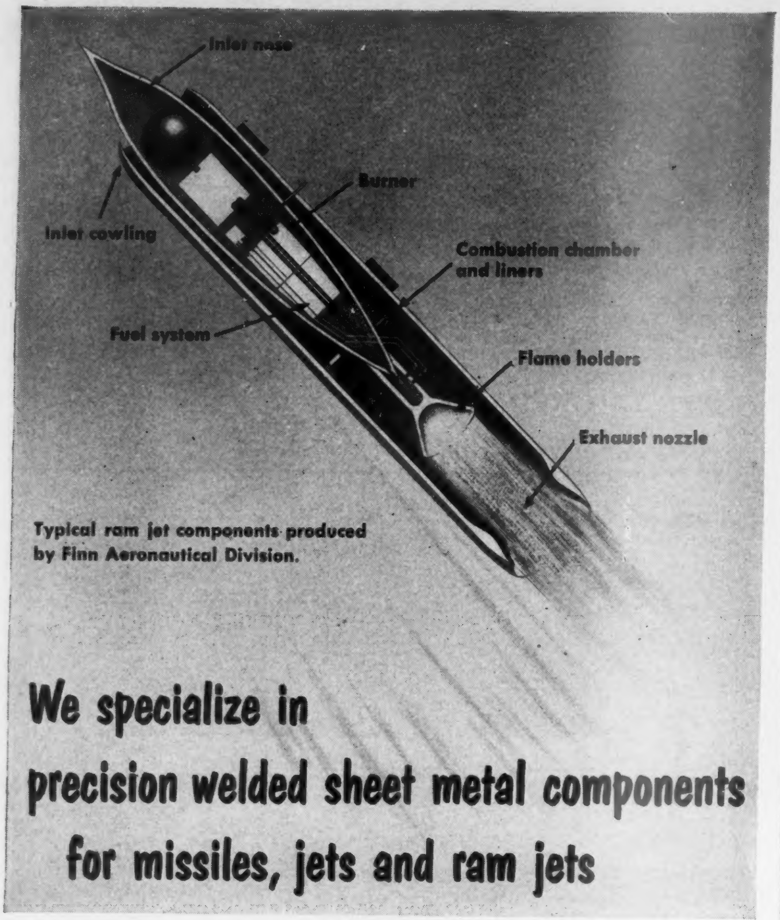

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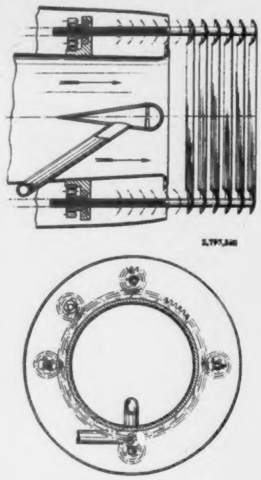
Jet propulsion combustion apparatus with expansively mounted fuel manifold (2,793,495). Harry C. Karcher, Indianapolis, Ind., assignor to General Motors Corp.

Fuel manifold extending around the upstream face of a flameholder ring. Fuel spray orifices are located in the manifold next to the ring. The manifold is supported on the ring with freedom for relative circumferential movement.



Thrust spoiler for propelling nozzles (2,797,548). R. H. Marchal, F. M. L. Maunoury, H. Turinetti and J. H. Bertin, Neuilly-sur-Seine, France.

Controllable means for displacing a set of concealed guide vanes into and out of a casing to deflect the jet stream from the axis of the propulsive nozzle.

Operating internal combustion burners of the jet motor type (2,794,316). Paul F. Winternitz, New York, N. Y., assignor to Reaction Motors, Inc.

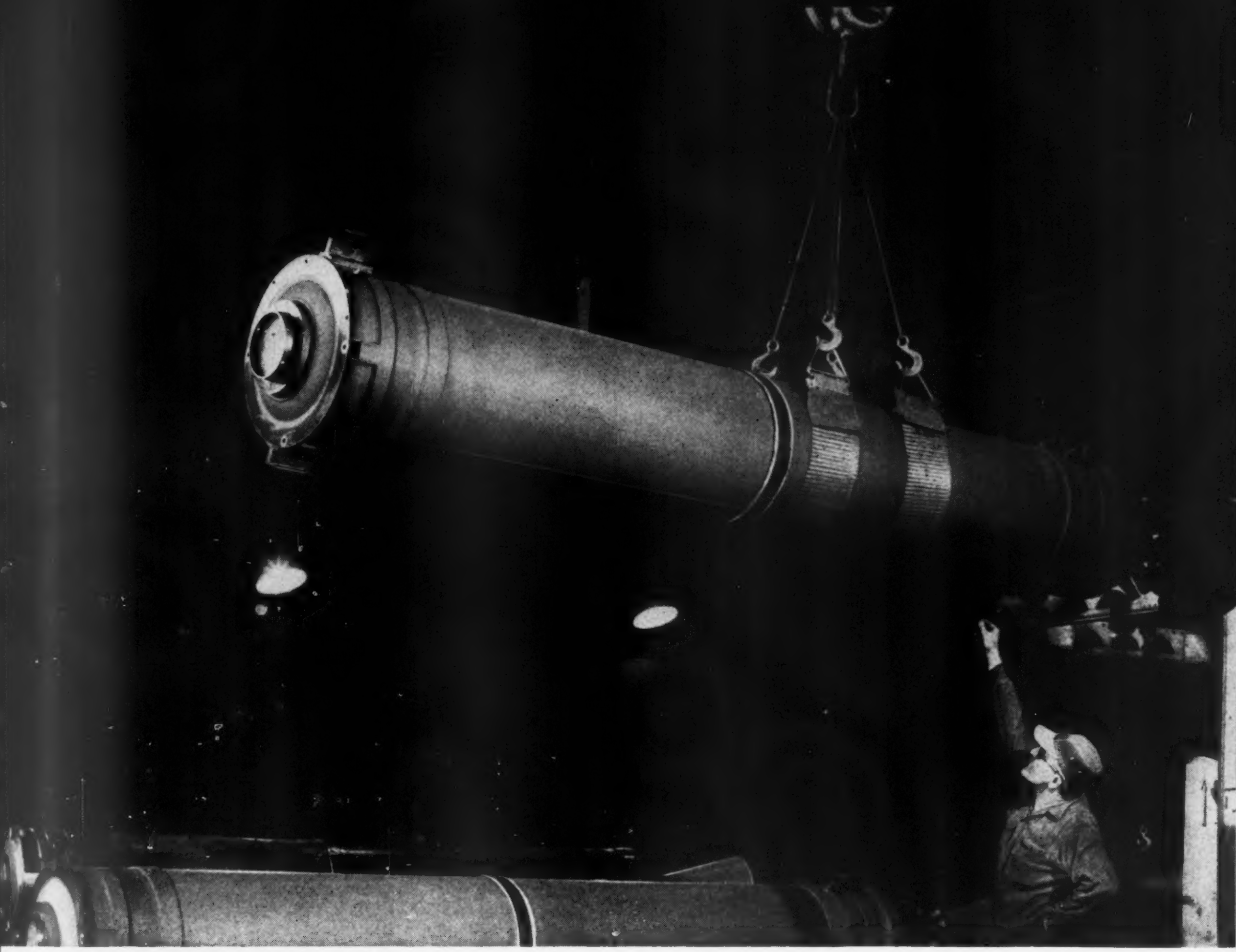
Method of protecting from burning out an internal combustion burner. Into the chamber is continuously and concurrently injected under pressure an oxidant and fluid fuel containing a substance which burns in the oxidant to form a refractory solid oxidation product. The amount of substance in the fuel provides deposition at a rate to maintain and renew the protective coating on the internal walls. The fuel is comprised of a monomeric lower tetra alkyl orthosilicate.

Jet propulsion nozzle apparatus (2,794,317). Charles R. Brown, Glen Mills, Pa., assignor to Westinghouse Electric Corp.

Variable area nozzle for a jet engine in which a group of master leaf elements are disposed about the discharge opening. Slave leaf elements cooperate with the master leaves to form a converging discharge nozzle. Elements are held in sealing engagement by pressure of the discharged fluid.

Propellant supply system for jet propulsion motor (2,794,318). Maurice J. Zucrow and Herman L. Coplen, Pasadena, Calif., assignors to Aerojet-General Corp.

System for introducing a liquid propellant into a motor chamber. When a solenoid operated valve is placed in one position, the pressure source and pilot chamber are interconnected and the throttle vent is closed. In its second position, the pressure source is disconnected and the pilot chamber is connected to the throttle vent so as to exhaust, thereby reducing pilot chamber pressure and increasing the pressure passing the regulator.



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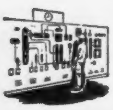
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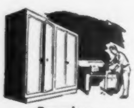
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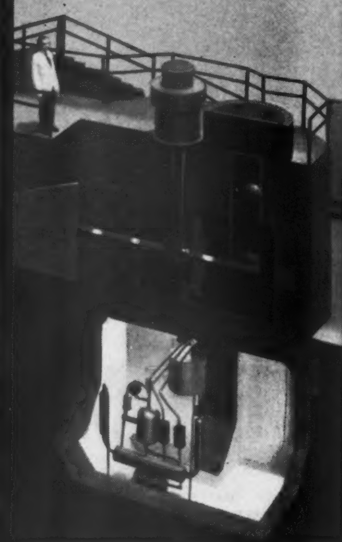

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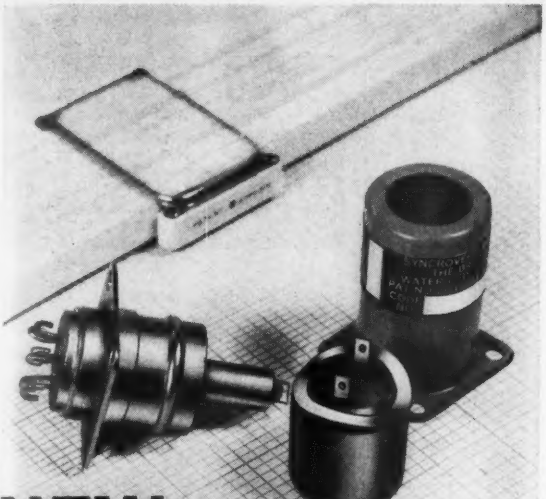

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***Phase Lag:**	60° ± 10°
***Dissymmetry:**	15° max.
***Switching Time:**	15° ± 5°
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Operating Position:	Any
Mounting:	Flange; 2-hole or 4-hole Plug-in; fits 7-pin miniature socket

*These characteristics based on sine-wave excitation, 400 cps.

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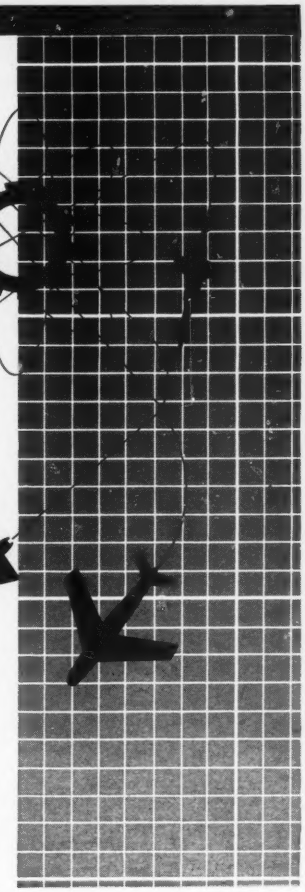

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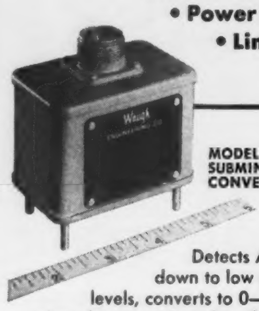

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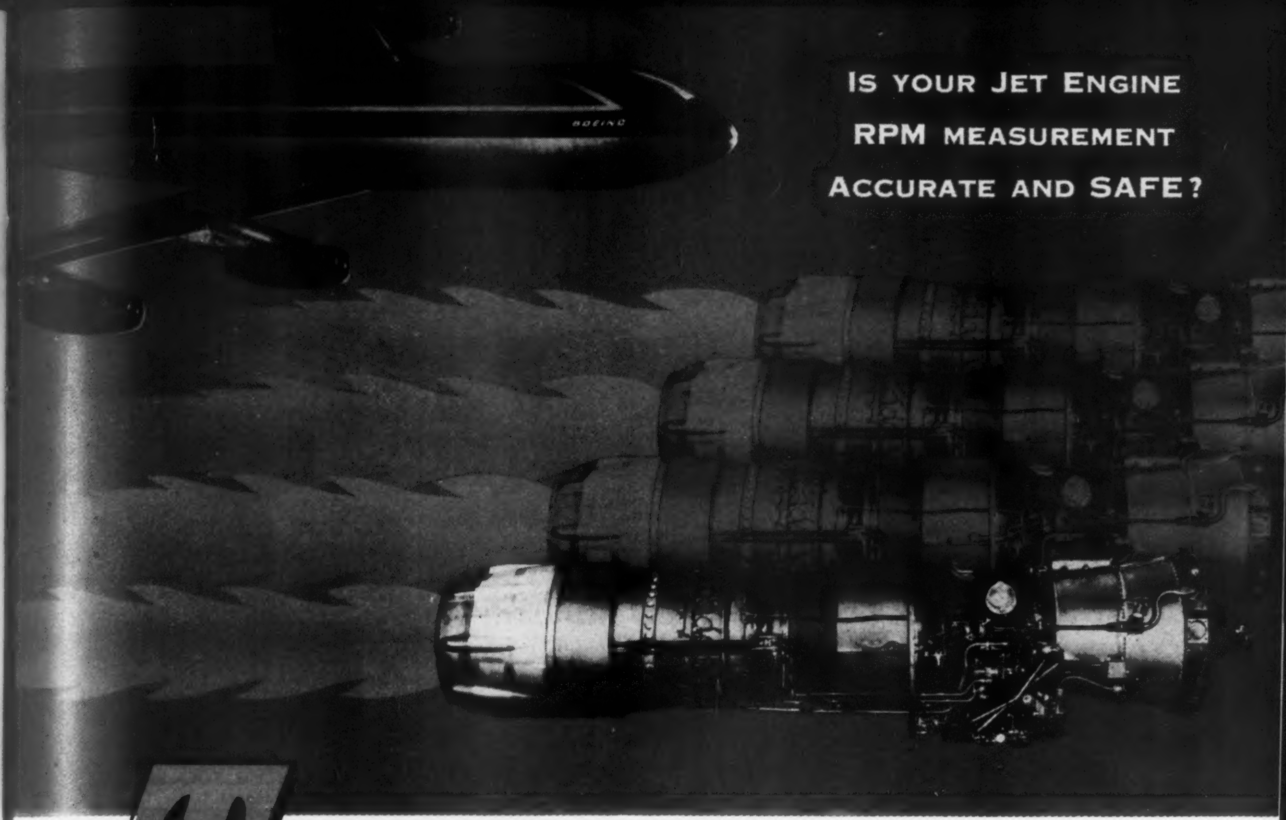

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The new B & H TAKCAL incorporates a refinement of the frequency meter principle. It operates in the low (0 to 1000 cps) range, reading the frequency of the tachometer generator on a scale calibrated in percent RPM corresponding to the engine's RPM. It reads engine speed while the engine is running with a guaranteed accuracy of ±0.1% in the range of 0 to 110% RPM. Additionally, the TAKCAL circuit can be used to trouble-shoot and isolate errors in the aircraft tachometer system, with the circuit and tachometer paralleled to obtain simultaneous reading.

The TAKCAL's component parts are identical with those used in the J-Model JETCAL Analyzer. They are here assembled as a separate unit tester and for use with all earlier models of the JETCAL Tester.

The TAKCAL operates accurately in all ambient temperatures from –40°F. to 140°F. Low in cost for an instrument of such extreme accuracy, it is adaptable to application in many other fields.

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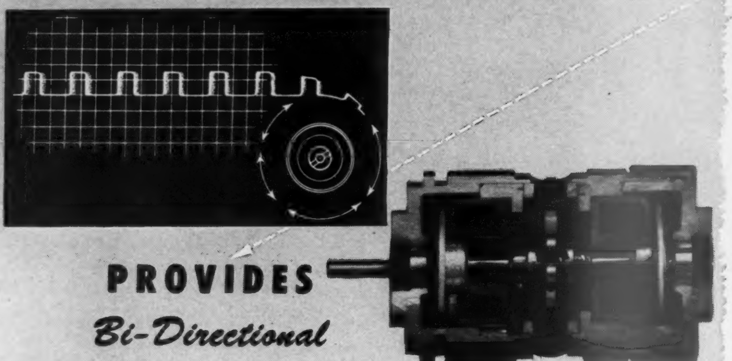
STEPPER MOTOR



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- Duty cycle — $\left(\frac{\text{on time}}{\text{on time \& off time}}\right)$ 56% max.
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- Shock — 15 G's for 11 milliseconds duration each way along three major axes.
- Reliability — shall not fail to convert more than one pulse in 1,000,000 into equivalent angular rotation.

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The two rotary solenoids contained in each motor produce the incremental motion of the output shaft in either direction. Energizing either of these solenoids produces a combination of linear and rotational motion which moves a ratchet gear axially into engagement with its mating ratchet gear and thus imparts a constant amount of rotation to the output shaft. The detent roller assembly insures constant, reproducible angular shaft rotation increments in either direction and maintains the output-shaft position while the motor is at rest with the power off.

Stepper Motors are adaptable to routine jobs such as driving mechanical counters. They also find excellent use in positioning devices that will set up a controlling voltage and/or a phase shift such as potentiometers and autosyns. They are widely used as a positioner for guided missiles to adjust heading, fuel flow, altitude, and circuit sampling for telemetering purposes. In one adaptation as a heading controller, two Stepper Motors are used to position a differential autosyn in steps of either vernier degree or coarse degrees per input pulse, bi-directionally, through a suitable gear train.

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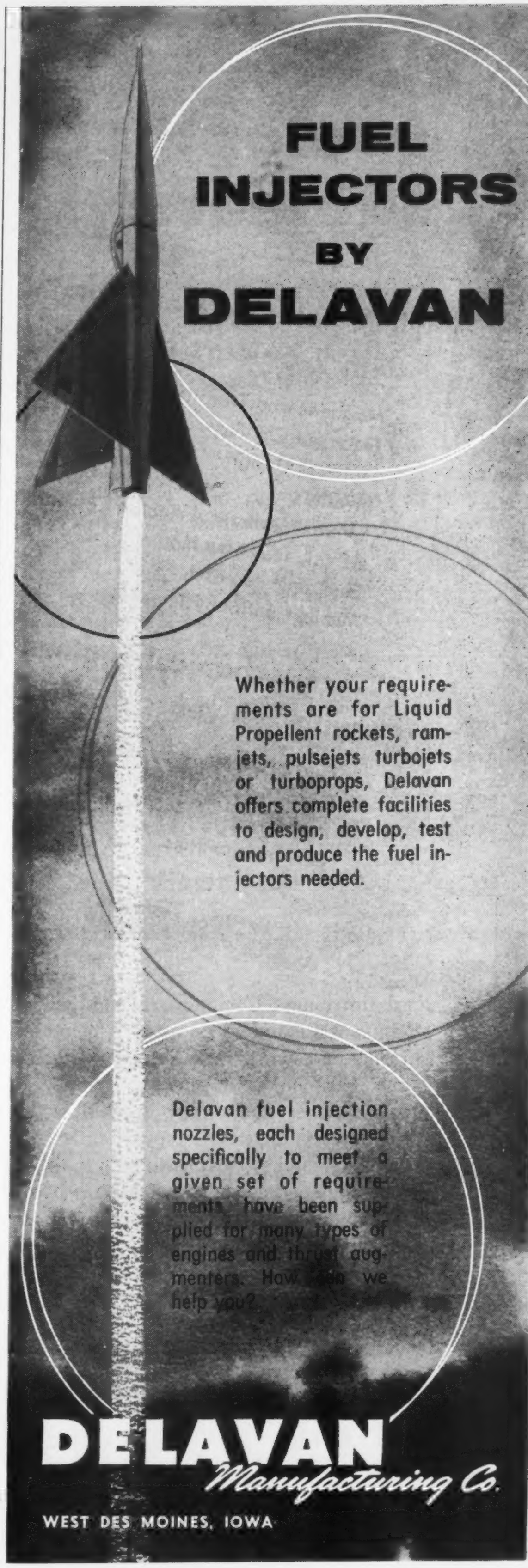

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CHARACTERISTICS

Recording System; Non-return to zero. **Drum Speed;** 2300 in. per sec. **Writing Current;** 70 ma. **Cell Density;** 100 bits per in. **Head to Drum Spacing;** .001 inch. **Drum Coating:** Red oxide, .001 in. thick. **Output;** 1 volt peak to peak. **Track Width;** .125 in. **Core Width;** .090 in.

The performance characteristics of Model MH15A can be incorporated in the MH10A case if desired.

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Specifically Designed for Reading or Recording on Magnetic Drum Memory Systems

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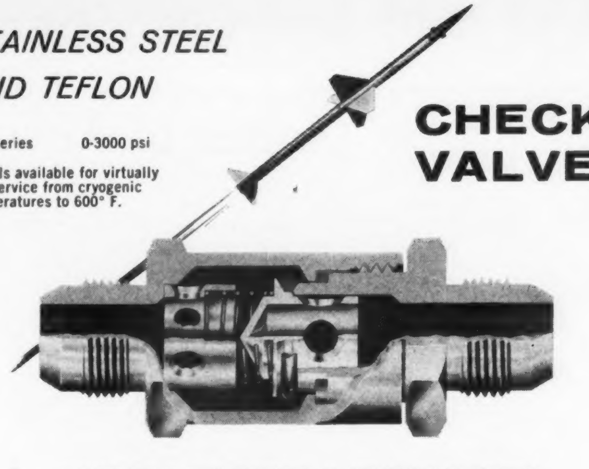

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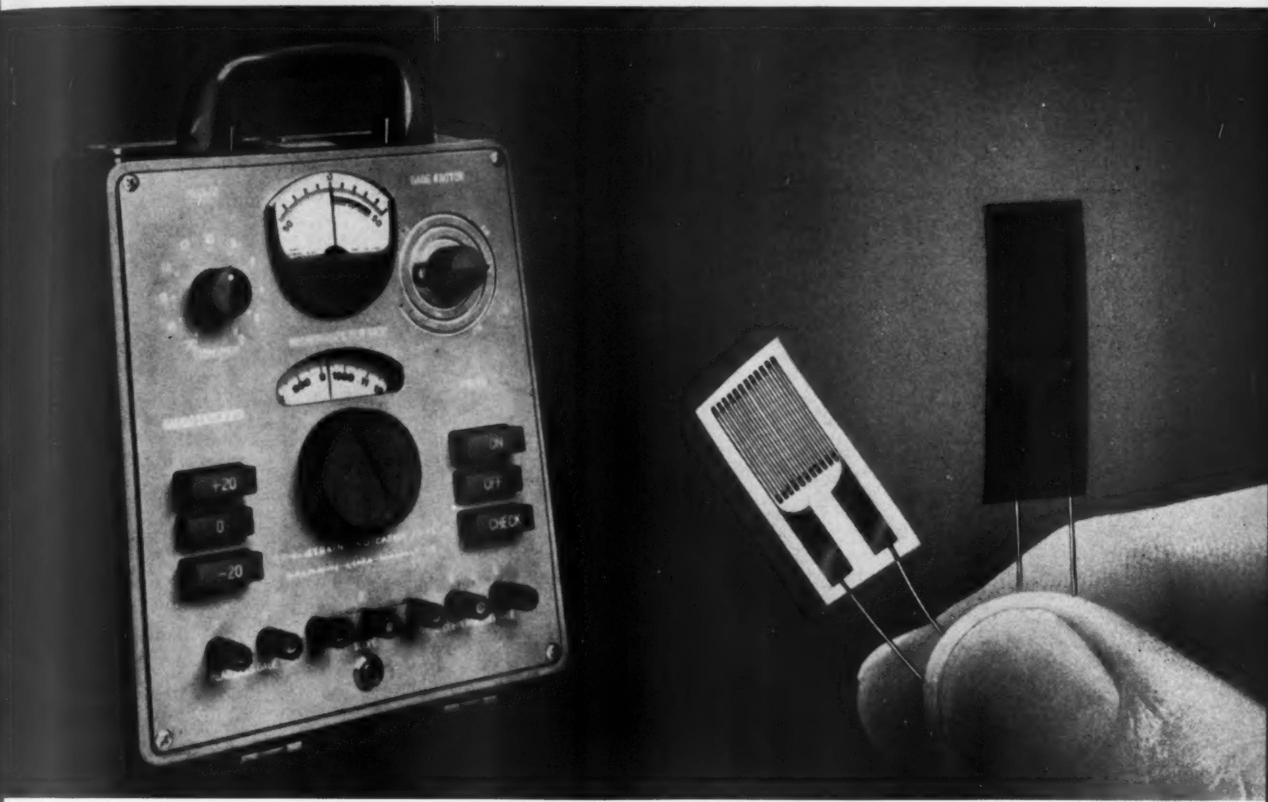
Newest strain-measuring equipment from Baldwin



Foil gages shown above are enlarged to twice their actual size.

NEW SR-4® strain indicator and NEW SR-4 bonded foil strain gages

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